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13th National Light Rail and Streetcar Conference

Transforming Urban Areas

November 15–17, 2015
Hyatt Regency Hotel
Mineapolis, Minnesota

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Cosponsored by
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Lea Camarda, Production Editor; Kristin C. Sawyer and Pat Spellman, Proofreading;
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Foreword

The 13th National Light Rail and Streetcar Conference: Transforming Urban Areas is the most recent in the Transportation Research Board (TRB) series on light rail that began in Philadelphia, Pennsylvania, in 1975. The American Public Transportation Association (APTA) became cosponsor in 1995.

At the Philadelphia conference the technical sessions focused on introducing the concept of light rail transit (LRT) in North America. Light rail had evolved from traditional streetcar systems in many northern European cities into intermediated capacity and performance rail transit systems scaled for midsized urban areas. The purpose of the first light rail conference was to show local decision makers in North America that the concept had great promise for application in North American cities. The then-Urban Mass Transit Administration (now the Federal Transit Administration) jointly sponsored the first conference and offered financing for cities willing to implement light rail. At that time there were only eight legacy streetcar systems left in Canada and the United States.

Now, 40 years later, the eight legacy systems have been rebuilt with many light rail characteristics and 20 new light rail and 10 streetcar systems have been built, totaling 38 new and rebuilt systems since 1978. Many of the new systems have steadily expanded through the years. Four additional streetcar lines are under construction and at least a dozen streetcar proposals are in the discussion stage.

The focus and related topics of the previous 12 national conferences have paralleled the development and reintroduction of LRT in North America:

- Introduction to LRT, 1st National Conference, Philadelphia, 1975;
- Light Rail Transit: Planning and Technology, 2nd National Conference, Boston, Massachusetts, 1978;
- Light Rail Transit: Planning, Design, and Implementation, 3rd National Conference; San Diego, California, 1982 (in July 1981, San Diego was the first all-bus urban area in the United States to open a new light rail system. In 1978, Edmonton, Alberta, was the first in North America);
- Light Rail Transit: System Design for Cost-Effectiveness, 4th National Conference, Pittsburgh, Pennsylvania, 1985;
- Light Rail Transit: New System Successes at Affordable Prices, 5th National Conference, San Jose, California, 1988;
- Light Rail Transit: Design and Operating Experience, 6th National Conference, Calgary, Canada, 1992;
- Building on Success, Learning from Experience, 7th National Conference, Baltimore, Maryland, 1995;
- Light Rail: Investment for the Future, 8th National Conference, Dallas, Texas, 2000;
- Light Rail: Experience, Economics, and Evolution: From Starter Lines to Growing Systems, 9th National Conference, Portland, Oregon, 2003;
- Light Rail Transit: A World of Applications and Opportunities, 10th National Conference and First Joint International Light Rail Conference, St. Louis, Missouri, 2006;

- Light Rail: Growth and Renewal, 11th National Light Rail Conference, Los Angeles, California, 2009; and
- Sustaining the Metropolis: LRT and Streetcars for Super Cities, 12th National Conference, Salt City, Utah.

The technical information in the proceedings of these conferences provides planners, designers, decision makers, and operators with a valuable collection of experiences and the ingredients necessary for a successful transit development process.

On November 15–17, 2015, more than 220 transportation industry experts met at the Hyatt Regency Hotel in Minneapolis, Minnesota, for the 13th National Conference. Sponsored by TRB and APTA and hosted by Metro Transit, the conference focused on how investments in light rail and streetcars can strengthen the entire transit network, contribute to regional mobility, and integrate successfully into the built environment. Sessions explored ways to plan, design, construct, maintain and operate light rail and streetcar systems. Positive results were showcased in metropolitan areas that have embraced light rail and streetcars.

The conference continued the themes of "inserting" LRT and streetcars into urban street environments and tracking the reemergence of streetcars that was begun in the 2012 conference. State of good repair, safety, infrastructure, and state-of-the-art vehicles were major themes. A session was devoted to developments in Canada, and a special panel discussion on successful practices in Eastern and Western Europe closed the conference.

Participants could take several tours: the Minneapolis Heritage Trolley Museum; Metro Transit's Blue Line, including the Hiawatha O&M facility; and Metro Transit's Green Line, including the Union Depot and St. Paul's LRV maintenance facility; and a products and service showcase.

—John Wilkins, *Chair Conference Planning Committee*
Stephen Andrle, *TRB Senior Program Officer*

NOTE: This introduction updates the historical introduction from 2012 written by Richard Krisak, then chair of APTA LRT Technical Forum, and Gregory Thompson, then Vice Chair of TRB Standing Committee on Light Rail Transit.

REFERENCES FROM PRIOR LRT CONFERENCES

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2. *Special Report 182: Light Rail Transit: Planning and Technology*. TRB, National Research Council, Washington, D.C., 1978.
3. *Special Report 195: Light Rail Transit: Planning, Design, and Implementation*. TRB, National Research Council, Washington, D.C., 1982.
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11. *Transportation Research Circular E-C145: Joint International Light Rail Conference: Growth and Renewal*, Transportation Research Board of the National Academies, Washington, D.C., 2010.
12. *Transportation Research Circular E-C177: Sustaining the Metropolis: LRT and Streetcars for Super Cities*, Transportation Research Board of the National Academies, Washington, D.C., 2013.

PUBLISHER'S NOTE

The views expressed in the papers are those of the individual authors and do not necessarily represent the views of TRB or the National Academies of Science, Engineering, and Medicine. The papers have not been subjected to the formal TRB peer-review process.

Contents

Complete Streets

Mitigation of Hazards for Street Running and Semiexclusive Light Rail Rights-of-Way

WALTER HEINRICH
Metropolitan Transit Authority of Harris County (Texas)

KEVIN JONES
LYNN SCHRAUTH
Parsons Transportation Group

Street-running rail transit systems were much more common in the early 20th century, but modern light rail and streetcar systems have reintroduced the challenge of inserting rail vehicles into the urban environment along with cars, buses, trucks, and pedestrians. How can all of the issues be mitigated? Houston METRORail has tried various engineering and operations changes to help reduce near misses and accidents: defensive driving training for operators; backplates, in-pavement lighting, and other traffic changes at intersections; working with the City Department of Public Works and Engineering on signage, striping, and traffic patterns; and partnering with stakeholders in creating safer environments for rubber-tired vehicles and pedestrians. Consideration must also be given for construction sites, special events, and track worker safety while workers are performing maintenance in a public right-of-way. Some changes were even implemented and removed before revenue service when they did not have the expected effect.

Interurbans and streetcars of yesteryear had to deal with mixed-use environments operating in city streets and with the growth of the communities they served. In many cases, this problem along with declining ridership caused by competition from bus lines was the impetus for closing several of these rail systems. Some of the first modern light rail systems built in the early 1980s and1990s—such as in San Diego, California; Salt Lake City, Utah; and Dallas, Texas—were designed to use former railroad rights-of-way or parallel existing railroads along with street running in the downtown area that made them look similar to an interurban of the early 20th century. In the past decade, many more street-running systems have come online and have had to deal with urban traffic and growth rather than corridors governed by the Federal Railroad Administration. This has led to a new set of hazards that an urban rail system must deal with—specifically, how to mitigate closer interactions with rubber-tired vehicles. Trying to install a rail system in an urban environment today requires an understanding of not only rail operations but also highway construction, the standards of the *Manual on Uniform Traffic Control Devices* (MUTCD) (*1*), and a working relationship with city public works or roads departments to institute improvements.

METRORail IN HOUSTON

METRORail opened the Red Line on January 1, 2004, after a 20-year battle with voters and politicians and more than 60 years after the last streetcar system in the city had closed. The new system was a 7.5-mi rail line that cost $324 million and was locally funded. It boasted 18 prototype Siemens S70 cars on a 6-min headway serving Reliant Park Stadium (now NRG), the Texas Medical Center, the Museum District, and downtown Houston (known as the central business district). The construction of the line put the rail system in a semiexclusive right-of-way with tracks in between lanes of traffic, with the exception of the southern mile of the line that has its own ballasted right-of-way.

Although the original system has more than 80 grade crossings, only 11 have grade crossing arms, with the rest protected by traffic signals for rubber-tired vehicles and bar signals for trains. The downtown section has multiple one-way streets, and trains operate through the middle of a specially designed water fountain. The Medical Center has some of the biggest challenges in that the rail line actually shares nine left-turn lanes with rubber-tired vehicular traffic; these are turn lanes for vehicles but tangent track for trains. This results in confusion for some drivers who get nervous seeing a train pull up behind them and instead make turns from an incorrect lane. One of these intersections with a shared left-turn lane in the Medical Center has accounted for 15% to 25% of all METRORail accidents annually. With the occurrence of five accidents during pre-revenue and 10 accidents in the first month of revenue operation alone, METRO relied on outside resources, such as the Texas A&M Transportation Institute (TTI), to help with accident reduction. TTI's recommendations focused mostly on signage and signal modifications, but many of the mitigations installed on the Red Line over time were used for the new extensions.

CHANGES BY METRO IN THE ORIGINAL ALIGNMENT: 2004–2008

Within the first year of operation, METRORail experienced more than 70 accidents involving rubber-tired vehicles and pedestrians. The following years were spent implementing various mitigations that reduced the number by half. The following are some of the issues that METRORail focused on to improve the safety of the system.

Defensive Driving

Because of the semiexclusive nature of the right-of-way, train operators are taught the same defensive driving techniques as METRO bus drivers. Operators are taught to be aware of their surroundings because practice has shown that pedestrians and drivers are not always alert to their environments. Although it is nearly impossible to eliminate all accidents when operating in such a tight right-of-way, defensive driving techniques can help reduce the severity of accidents by helping operators prepare for the actions of others.

Signal Priority

When it originally opened, the train would automatically receive a proceed signal from all the bar signals needed to get through downtown. However, this enraged some drivers who not only would get stuck waiting for a train but had previous perceptions of accident-prone trains. The City changed the system back to one that gave trains a favorable bar signal at the same time as the vehicular traffic. This led to an increase in accidents caused by those who made illegal left turns off Main Street in front of trains—turns that were illegal before the rail system was even built.

The signal system has been revised several times, but the most effective method has been once cross-traffic has been stopped and a train is waiting to proceed or is approaching the signal, then the opposite direction traffic signal receives a green light while the traffic signal parallel to the direction of the train remains red until the train clears the intersection. This method is currently known as "predictive priority," and Figure 1 demonstrates how this works.

This method has helped reduce the incidents of rubber-tired vehicles making left turns in front of trains when both have received a green light–proceed signal simultaneously. Since introducing this method several years ago, only two left-hand turn accidents have occurred in the downtown area of the Red Line.

(a)

(b)

(c)

FIGURE 1 How predictive priority works: (*a*) Southbound train proceeds. Northbound train bar signal at a stop. Northbound traffic has green light. (*b*) Northbound train bar signal shows a proceed signal. Northbound traffic has a stop (note the LED backplate around the traffic signal because of crossing a green–purple line at this intersection). (*c*) Northbound train has cleared the intersection and bar signal at a stop. Northbound traffic again receives a green light.

LED Backplates and In-Pavement Lighting

The start-up of the Red Line in Houston in 2004 also created a requirement for drivers to watch out for a 50-ton train operating next to them. In-pavement lights were installed in a row in the street just past the stop line at several intersections to make motorists aware of a red traffic signal before crossing the rail line. LED backplates were also installed to light up a red ring around the traffic signal to make it more distinctive from other traffic signals in the city (see Figure 1). These changes were made to several test intersections starting in March 2006 for the in-pavement lights and in November 2006 for the LED backplates. A follow-up study by the TTI showed a statistically significant reduction in illegal vehicular movements along with a reduction in accidents at those intersections where the LED backplates and in-pavement lights were installed (*2*). However, the in-pavement lighting proved to be too much to maintain (and Houston does not have snow plows). Despite a change in vendors, the in-pavement lights were eventually disconnected after the vendor cancelled the contract. LED backplates are still used by METRO; they are built by a contractor and installed by the City of Houston Department of Public Works and Engineering. The cost to make and install three to four LED backplates per intersection is roughly $7,000.

Signage and Striping

Signage to warn motorists usually comes in the form of advanced warning sign, cross bucks, or something similar showing a road crossing a railroad track. The MUTCD governs usage and size of highway signs, but sometimes other variations are used. Static signage is not always the most useful, especially when an area is cluttered with parking and directional signage on overhead arms and street poles.

Active signage was installed at multiple locations, such as the entrance to a turn lane. Two types of signs have been installed: A Light Rail Activated Blank-Out sign (MUTCD W10-7) shows the picture of a train and flashes when a train is on approach in either direction. The other sign is a combination green arrow or red ‘X’ that lets drivers know when it is safe to enter the turn lane or when to stay out because of a train on approach.

Striping can also help better direct traffic on where to go. The transit agency needs a working relationship with the city’s department of public works and engineering to ensure striping is maintained and a way to report issues quickly.

Turn Lanes

Streetcars and other shared rights-of-way not only have to deal with rubber-tired vehicles coming in and out of their lanes or crossing in front of them but also traveling in a direction different from vehicular traffic. The Texas Medical Center is the world’s largest medical complex; it hosts 21 hospitals, support organizations, research institutions, and eight universities or medicine-related schools in an area slightly larger than 2 square mi and has more than100,000 employees and over 7 million visits per year. The addition of METRORail in this area required some compromises to allow traffic to continue to flow, such as having the right-of-way operate through left-hand turn lanes. These lanes are marked by signage and controlled by active signs that switch from a green arrow to allow traffic to use the turn lane and a red ‘X’ that advises when a train is coming. In-pavement lights were also installed as an additional measure to prevent rubber-tired vehicles from entering the turn lane in front of a train. However, their purpose was difficult to understand by drivers, and they were later removed with collapsible bollards remaining to delineate the turn lane and create a specific point of entry for rubber-tired vehicles to make a turn. These bollards are sturdy and help drivers maintain their lanes, but the bollards are flexible enough for an emergency vehicle to run over them without causing damage to the bollard or rubber-tired vehicle.

Shared turn lanes also created an issue for pedestrian crossings. In a signal cycle for a shared turn lane, it is impossible for both turn lanes to clear out at the same time because of trains moving forward in a straight line and thereby causing a conflict with the opposing turning traffic. The signals at these turn lanes have additional signal phases in them:

1. Eastbound traffic has all green.
2. Westbound traffic has all green.
3. Southbound has all green.
4. Southbound and northbound straight traffic has all green with turning traffic at stop.
5. Northbound traffic has all green.

Normally, Step 4 could be eliminated and allow only one direction of movement at a time. But the volume of traffic travelling straight requires this signal phase to eliminate traffic backups. The issue is that pedestrian movements act as a sixth phase for the traffic signal and cause extreme delays for pedestrians waiting for traffic, with many of them taking risks at jaywalking across a busy street. The solution worked out between the Texas Medical Center, METRO, and the City of Houston Department of Public Works and Engineering was to allow a split pedestrian signal so that pedestrians could cross halfway on signal Phases 3 and 5. For example, when Step 3 occurs, pedestrians can now get a signal to cross only the northbound lanes of traffic to the middle of the street to access a rail platform. This is similar to Step 5 that enables them to cross only the southbound lanes of traffic. This has reduced the wait time for pedestrians along with issues of jaywalking.

Pedestrian Poles and Fencing

Although accessibility is important in getting to and from public transportation, allowing free access is another problem altogether. One issue seen in Houston is people stepping down from the platform and walking across the tracks and through traffic to the sidewalk rather than following established pedestrian pathways. METRO installed a series of metal pedestrian poles between the street and the trackway at platforms that were drilled into the ground with wire cable connecting them. The poles were meant to deter people from crossing the tracks illegally and instead use the crosswalks. In general, these poles have been effective in directing people to the exits, and the only issues have been from errant vehicular traffic coming in contact with the poles and bending or breaking them.

Traffic Buttons

With 95% of the METRORail trackway embedded next to a street, it can become difficult for drivers to differentiate the street from the railway. The original 7.5-mi alignment used a brick design in the concrete to differentiate the trackway from the street, but rubber-tired vehicles could still easily drive on the tracks where they should not. Additional concrete dome forms, known as “traffic buttons” because of their shape, have been placed between the lane of traffic and the street to give drivers a “rumble strip” feeling when they veer too close to the tracks. These traffic buttons are glued down to the concrete base poured for the trackway, but occasionally, they become dislodged or even crumble and break underneath sufficient pressure. They are easily replaced yet heavy enough to not make good projectiles when they become loose.

The other use for traffic buttons has been to place them on the top of curbs close to the trackway so that people will find it inconvenient to sit on the curbs. This was a serious issue near the Main Street fountain where the street is blocked by a curb next to the tracks. The traffic buttons have been used to discourage people from sitting on the curb in such a hazardous condition.

Pedestrian Mall

Although it is not what most would consider a pedestrian mall, downtown Houston has a couple of blocks at which pedestrians can cross the tracks without having to worry about crossing the street. The first block of this “mall” has only planter boxes between the sidewalk and trackway, while the second block has a large water fountain that the trackway runs through. Timers and train detection devices are used to prevent the fountain jets from operating while the train passes. At either end of the fountain and the adjacent blocks, pedestrians are prevented from crossing the tracks by only pedestrian signals, and pedestrian incursions occur frequently in this area for various reasons. Rubber-tired vehicles also end up in the fountain from time to time despite bollards attempting to prevent them from taking a bath. The planter boxes work well as an intrusion barrier, and although operating an electrical-powered train through a water fountain is counterintuitive, it also acts as a barrier between pedestrians and trains. A continuing issue is at the crosswalks; here the lack of a street crossing tends to reduce pedestrian attentiveness. Train operators tend to use their audibles (gong, whistle, horn) while travelling through this area.

Work Crews and Roadway Worker Protection in a Street-Running Environment

METRO work crews must deal with a variety of issues other than just working in the trackway. Rubber-tired vehicular traffic is never far away, and other than traffic buttons and a slight elevation difference between the street and tracks, nothing really protects work crews from an errant rubber-tired vehicle. Work crews must follow track worker safety procedures closely and always have a safe location to move to to allow traffic or trains to pass. An additional issue with street-running environments is the use of, or lack of, interlocking signals that can also be used to protect workers. Rail controllers must be vigilant to ensure that all operators are aware of the work crews and have personnel ensure that slow zones or work zones have been installed properly. Supervisors and safety personnel check to ensure that work crews are up to date on track safety, possess a track access permit, and have proper signage in place.

In school zones, crossing guards need to be taught proper safety protocols around trains, whether they operate in the street under traffic laws or operate in a semiexclusive right-of-way. A modified track safety process, fit to their needs, is one of the best ways to provide additional safety protection on the ground.

THREE NEW ALIGNMENTS: 2008–PRESENT

A referendum in late 2003 voted to install bus rapid transit in several corridors first and upgrade to rail lines later, but by 2007, the decision was made to make them all rail lines from the beginning. Groundbreaking occurred in June of 2008, but two of the five rail lines were later shelved for various reasons.

The Parsons Transportation Group led a Houston Rapid Transit (HRT) joint venture that involved designing and constructing the three new light rail transit corridors, which entailed civil works components, associated light rail transit communications, and signal and traction power systems. The project scope also consisted of roadway betterments, stations, guideway, two maintenance and storage facilities, and several major and minor bridges. Parsons also provided system safety and quality assurance services and managed the community outreach and small business participation programs for the overall project. The total length of the project is approximately 15 mi and includes 24 stations.

The opening of the north corridor in December 21, 2013, added an additional 5.3 mi, 14 more grade crossings of which two are gated crossings, and two bridges built over freight railroads. One of these bridges has METRORail's first aerial station and was the focus of training for the Houston Fire Department. Most of the north corridor is similar to the existing Red Line with a semiexclusive right-of-way in between lanes of traffic with the exception of the two bridges, which are rail only.

The east and southeast corridors opened May 23, 2015, and added another 9.9 mi with a mix of semiexclusive right-of-way, exclusive right-of-way, and street-running operations. The east corridor has an additional seven crossings with only the Yard Lead having gates and is completely semiexclusive right-of-way. The southeast corridor added 22 crossing with only eight of those with gates and is mostly semiexclusive right-of-way, though the roughly 3/4 mi of exclusive right-of-way is concrete instead of ballasted. The downtown section where the two new lines operate jointly is the most interesting. Starting on the east side of town near the Minute Maid ballpark, the tracks enter into a one-way street and continue approximately 1.2 mi to a turnback track located on a bridge over the Buffalo Bayou. Trains then return eastbound on a one-way street one block south of the westbound track. In each direction the train operates with traffic in the street sharing a lane of traffic with three station stops and crossing the Red Line at grade. Further compounding the issue is the fact that the shared lane is the designated turn lane for 11 intersections and provides access to 10 parking structures, 11 surface parking lots, and four loading docks. At peak periods, including for special events, the frequency of this rubber-tire vehicle and light rail vehicle (LRV) interface increases significantly and enhances the potential of an incident. Couple this additional interface with the normal jockeying for position by rubber-tired vehicles, and a design issue must be addressed, along with operational procedures to be implemented to reduce the probability and severity of an occurrence.

HRT was tasked to deliver an efficient, yet safe, design in this area. To the extent possible, HRT used the preliminary hazard analysis that was completed in 2009 to identify similar hazards. Because this issue was new to METRO, the full complexity was not analyzed at that time. To move forward with establishing a safe design, it was decided that a more detailed hazard analysis would be required for certain items.

Mitigation for a Shared Lane of Traffic

The operation of a light rail vehicle sharing a right-of-way with rubber-tired vehicles, while not unheard of, led to some anxiety that was based on knowledge of operations and accidents with shared turn lanes in the Texas Medical Center. To establish what needed to be analyzed, HRT began to coordinate a number of joint discussions with the design team, METRO officials (including Safety), and other traffic consulting firms. The primary objective was to establish any issues that needed to be reviewed within the project scope. The issues that required further hazard analysis included the following:

- Use of shared lanes with rubber tired vehicles, in general;
- Interface of automobiles exiting adjacent parking lots and structures;
- Interface of a federal prison bus that has designated parking adjacent to the shared use lane and discharges into the lane; and
- Interface of commercial vehicles that utilize drop-off points or existing loading docks adjacent to the shared use lane.

From these cooperative discussions, METRO was able to provide HRT with a better understanding of similar conditions along its existing Red Line and how it mitigated those hazards. In some cases, the existing mitigations were utilized while other mitigations proved to potentially cause more issues. For instance, active warning signs were used previously in similar conditions in which a parking structure let out onto the roadway. However, that condition was not in shared use but occurred when rubber-tired vehicles had to cross the tracks in a perpendicular fashion.

After initial development of the hazard analysis, it was determined that further background information was needed. Of greatest concern was inclusion of additional signs, whether static or active, that may create sight obstructions for exiting rubber-tired vehicles. By mitigating one hazard, an additional hazard could be potentially created with greater probability of occurrence.

HRT, through their local traffic engineers, conducted a line of sight study for all locations that will exit onto the shared use lane. To qualify this study, the sight lines were taken at 5 ft back from the curb for automobiles and trucks and 8 ft back from the curb for commercial vehicles. This stand-back distance demonstrated location of the driver when attempting to merge into traffic. The criterion for acceptable sight distance was at least 360 ft and was based on existing City of Houston criteria. Of the 24 locations studied, it was determined that 22 had sufficient sight distance equal to or greater than 360 ft. If during this study, trees or other landscaping were found to become a sight obstruction, that was noted and those obstacles were removed.

From the line of sight study, it was determined that only the two locations that did not have at least a 360-ft sight distance would have active signs included in the design. These active signs were located in a position so as to provide warning to rubber-tired operators but not impede their sight lines. For all other locations, simple static signage, outside of the sight lines, would be installed.

One of the other concerns about installation of active signs at all locations was the points of detection and activation by the LRV. A worst case scenario for activation would have to be designed; however, the presence of traffic congestion in the area would activate these signs for longer than needed and possibly create confusion for other motorists.

To assist with development of mitigations, Parsons and HRT staff also talked with safety and operations groups in cities such as Denver, Colorado, and Pittsburgh, Pennsylvania, which have existing shared use lanes. Many of the mitigations identified during the HRT and METRO discussions have been implemented by other agencies with proven success.

Other mitigations that were identified included the following:

- Elimination of access and egress points from parking lots. Through communication with the lot owners, the hope was to divert traffic from the parking lot to an adjacent street where they would utilize the existing traffic control signals to join the shared use lane. This was difficult as some lots did not have access capability from adjacent streets.
- A public awareness campaign for all motorists who travel in the downtown (or near any of the new corridors). Education of the public who frequent that area is of utmost importance. Parsons, along with HRT, developed and implemented a robust public awareness campaign and worked with local schools, community groups, and stakeholders to provide information and educational sessions.
- Robust LRV operator training program to prepare operators for shared use operations. This program should involve more defensive driving techniques and preparing for the unexpected.
- Updated rules and procedures for LRV operations. One of the suggestions from the hazard analysis was to implement a reduced speed limit for LRVs in the shared use lane. The speed limit for this area is 25 mph for LRVs, while rubber-tired vehicular traffic has a speed limit of 30 mph. Additional discussions took place about lowering LRV speeds to 20 mph because a decreased speed will have a shorter stopping distance in the event of an emergency or being cut off by a rubber-tired vehicle. This mitigation was not implemented.

An example of the hazard analysis used is shown in Figure 2.

The coordination and early discussion between Parsons, HRT, METRO, and its stakeholders helped to identify potential hazards during the design phase and allowed sufficient time for a thorough analysis and discussion of the hazards. HRT was able to design mitigations to reduce the level of probability of occurrence within these areas while helping improve current mitigation efforts to make them safer.

Pedestrian Poles and Fencing

The original fencing focused on directing pedestrians on and off platforms. The three new alignments presented new potential hazards such as five elementary schools, two large city parks, two sports stadiums, and the University of Houston and its new football stadium. With the possibility in mind of large crowds and groups of children trying to get across the trackway to schools, parks, and stadiums, it was decided to install fencing along the right-of-way to discourage trespassing. The original pedestrian poles that had been installed were metal with wire strands, but the hazard analysis from Parson identified that this setup did not account for an overhead contact system teardown that could energize the fence since it was not designed to be grounded. In reviewing the need to ground the pedestrian poles, along with construction and maintenance issues needed to bore holes for all the posts, the new fences would use fiberglass

HRT — **Preliminary Hazard Analysis (PHAs)**

Category: Traffic Interface

UN = UNACCEPTABLE, UD = UNDESIRABLE, AC/WR = ACCEPTABLE W/REVIEW

Reference #	Hazard Description	Potential Cause	Consequences	Initial Rating	Recommended Mitigation	Actual Mitigation	Final Rating
	Motor vehicle interface with LRV at road access points within the shared one-way lane along the right-of-way. (parking garage and surface parking lot exits, loading docks)	Lack of signage or warning devices to alert motor vehicle driver of shared one-way traffic pattern with LRV Excessive speed by the LRV Impatient motor vehicle driver tries to beat the LRV. Poor lines of sight (vegetation and signage) Motor vehicle driver not familiar with local traffic patterns and mixed use environment LRV operator not trained properly LRV operator distracted	Collision Injury Loss of life Service delay or interruption Equipment damage	IC UN	Signage based on TMUTCD at each access point Rules and procedures for LRV operators to follow posted speed limits or reduced LRV speed limit (reduces braking distance) Improve clear lines of sight Eliminate as many of the access points at parking lots as feasible Rules and procedures for safe operations LRV operator training program Public awareness program Advance warning of approaching LRV	Proper static signage, in compliance with TMUTCD will be installed METRO will develop rules and procedures for operations within shared used lanes Recommend to METRO that LRV speed be reduced to 5mph less than rubber tire speed limit in shared use lanes Assessment of clear lines of sight will be completed and make recommendations to enhance if needed METRO will develop training program for LRV operators within shared use lanes Public awareness campaign will be conducted prior to use of shared lanes	ID

Frequency of Occurrence	Hazard Categories			
	I Catastrophic	II Critical	III Marginal	IV Negligible
(A) Frequent	1A-UN	2A-UN	3A-UN	4A-AC/WR
(B) Probable	1B-UN	2B-UN	3B-UD	4B-AC/WR
(C) Occasional	1C-UN	2C-UD	3C-UD	4C-AC
(D) Remote	ID-UD	2D-UD	3D-AC/WR	4D-AC
(E) Improbable	IE-AC/WR	2E-AC/WR	3E-AC/WR	4E-AC

Hazard Risk Index	Acceptance Criteria
1A, 1B, 1C, 2A, 2B, 3A	UN-Unacceptable
1D, 2C, 2D, 3B, 3C	UD-Undesirable (decision required)
1E, 2E, 3D, 3E, 4A, 4B	AC/WR-Acceptable with review
4C, 4D, 4E	AC-Acceptable without review

FIGURE 2 Hazard analysis matrix.

poles with plastic chain link. Although it would require higher maintenance when struck by a rubber-tired vehicle, it would also be easier and cheaper to replace.

Signal Priority

When a train operates in the street with traffic, it can either proceed with the traffic signal or have a separate bar signal that is synchronized with the traffic signal. Only at a station platform at which a train can pull all the way up to the signal without interference from rubber-tired traffic does a train get its signal before that of traffic, which allows it to get a queue jump ahead of traffic. In two locations, trains must deal with a double left-turn lane at which the train is in the far left lane and both that lane and the lane to the right of the train can turn left. These lanes are located at stations so that traffic can go around the train while it boards passengers, and then the train receives its own signal to proceed while all traffic has stopped. Although it appears similar to the shared turn lanes in the Texas Medical Center that cause so many problems, with the adjustment between bar signals and traffic signals in the double left turn lanes, no accidents have occurred in this situation.

Curbs in the Street

Despite being an in-street rail operation, at certain locations additional curbing was installed between lanes of traffic to prevent rubber-tired vehicles from making turns in front of the train. This was tried in two locations to prevent rubber-tired vehicles from trying to enter a parking garage from the wrong lane and making a sudden turn in front of a train. At the entrance to the first parking garage (Figure 3), a curb was installed along with a sign directing rubber-tired vehicles to use the trackway to enter the parking garage. However, a pedestrian crosswalk across the street was located at this entrance that necessitated a break in the curb. Drivers would then use this gap in the curb as the location to make the right turn into the garage rather than driving in the lane shared with the track. It was decided to remove the curbing in both locations, since it only added to confusion, and once removed, traffic then took the desired action of turning from the proper lane.

Construction Projects

In addition to construction and maintenance of the railway and its own infrastructure, an urban railway has to deal with construction projects going on in the city at the same time. There are currently 41 major construction projects in the central business district of Houston; 22 of these are adjacent to one of METRORail's alignments, and another five are within one block. Although similar work is done in midtown, the Museum District, and the Texas Medical Center, the size and complexity of projects are much larger in the downtown area. In the past 12 months, METRORail has been affected by two building implosions, construction of a pedestrian tunnel

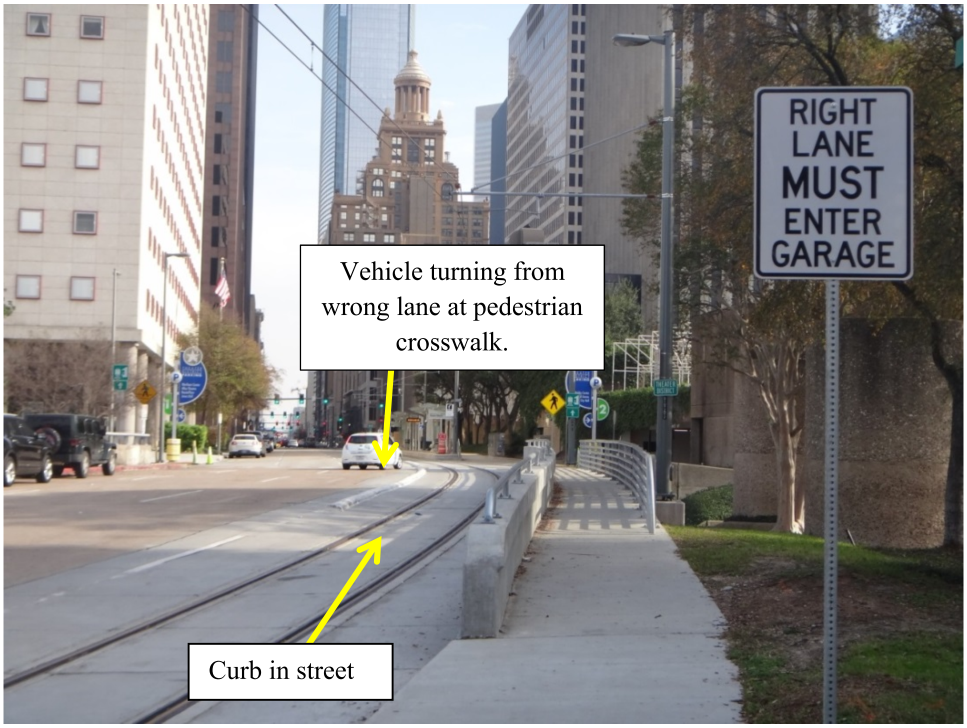

FIGURE 3 Issues with in-street curbs.

underneath the right-of-way, and construction of a parking garage–hotel–office building structure over the right-of-way. Construction is already under way for several buildings that are 20 stories or taller, including a 48-story building adjacent to the junction of the Red Line with the new east–southeast alignment. These activities have all required coordination with construction crews and contractors to coordinate service shutdowns, receive track safety, and go through the track allocation process in which contractors request authorization to work inside the METRORail safety zone. This is currently considered as the area within 15 ft of the center line of track or from curb to curb within street-running areas. Construction contractors must meet all the requirements for city permits and approvals. Additional consideration for an electrified rail line include grounding of scaffolding; pedestrian entrance and exits, including emergency evacuations, from station platforms; sight lines and elimination of temporary blind spots; and track safety training for construction crews. METRO has recently created an adjacent construction manual so that contractors are aware of what requirements they must meet when submitting bids.

Community Outreach

With the help of Parsons and HRT, METRO pushed forward with a multifaceted outreach campaign. This involved direct face-to-face meeting with stakeholders and residents, a rail safety flyer inserted into utility bills, and a series of meetings with schools and civic clubs. Many of these meetings were either part of the National Environmental Policy Act of 1969 process or a follow-up to community concerns. METRO had the local electricity supplier put safety notices in the utility bills of those who live near the rail line for local awareness. Presentations to schoolage children were twofold; the first concerned construction safety while the new lines were built, and a second, follow-up presentation was given about safety around the trains. Elementary school children were also given coloring books with safety messages. Crossing guards have been track-safety trained to prevent conflicts between trains and children crossing in school zones.

Stakeholder Input

Several stakeholders with parking garages or surface lots were interested in adding some additional signage to help warn motorists of approaching trains. On the basis of HRT's hazard analysis, these lots already had line of sight distances that met the 360 ft visibility requirement and trying to tie sign activation into any type of LRV location device would have been sporadic at best. Moreover, the City of Houston was not in favor of adding any additional signage to the curb. Most of these stakeholders ended up adding their own static signage stating "Watch for Trains," and some even added flashing yellow lights that blink constantly, whether a train is approaching or not. These were all installed at the expense of, and maintained by, the property owner.

LESSONS LEARNED AND ONGOING MITIGATION

In the original mitigation, signal priority and LED backplates were the strongest mitigations for reducing accidents. Signal priority almost eliminated illegal left turns in the downtown area, while LED backplates helped to statistically reduce red-light-running accidents. In-pavement lights were also a statistical winner, but since the product itself was unsuccessful, METRO moved ahead with the addition of LED backplates at those intersections at which the in-pavement lights were disconnected. Similar signal priority is of great interest for the Texas Medical Center to eliminate accidents from illegal turns; however, because of the layout of the intersections, giving the trains priority would require a signal cycle of greater than 120 sec, so it has not been implemented. The new alignments focused on using signal priority in double turn lanes to keep traffic moving and avoiding conflicts with trains.

Community outreach is also an ongoing mitigation with plans to create "how-to" videos on using the system and what to do when driving a rubber-tired vehicle in a shared lane of traffic. Track safety training will continue in schools, with crossing guards, and with construction crews.

In following up the Parsons hazard analysis, new pedestrian poles and fences were either replaced with fiberglass poles and plastic chain link or were grounded properly. New alignments have pedestrian fencing at stations, in school zones, and in high-traffic areas.

Some curbs were found to be more confusing than helpful and were removed before pre-revenue service. Public works and roads departments can help by setting up signage or improving striping and pedestrian and traffic signals in regard to their timing and priority.

Successes and failures for one location do not always translate to other locations or properties. Mitigation for street-running and semiexclusive rights-of-way requires knowledge not only outside of railroad operations but also of the MUTCD and construction needs as well as a working relationship with a city's public works or roads departments to make improvements to roads and signals.

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Inserting Streetcars into Pedestrian Areas

French Examples

DOMINIQUE BERTRAND
Centre d'Etudes et d'Expertise sur les Risques, l'Environnement, la Mobilité et l'Aménagement, France

The "streets for all" concept has been widely applied for several years in France. This concept aims at establishing a more balanced use of public space, by promoting active modes of transportation and reducing the prominence of cars. One of the main achievements of embracing this concept has been the implementation of traffic calming measures in designated areas; these include pedestrian zones and pedestrian priority zones, which have been institutionalized by the Street Use Code decree in 2008.

In the meantime, the renewal of tramways is happening in many large French cities; generally crossing city centers, most French tramway networks partially encroach upon significant pedestrian areas. Various contexts and causes may lead to this situation. However, in all cases, some adaptations of the configuration and ways of operating are required to make tramways successful and safe for all users.

The particular status of streetcars in regard to road rules is an advantage; however, some other key factors have been identified as facilitating the smooth insertion of streetcars within such areas. Among these factors, a clear identification of the gauge limits and the effective removal of car traffic in such zones are essential. When this is achieved, insertion of tramways may indeed be successfully implemented in various configurations of downtown pedestrian zones.

BACKGROUND

French Streets for All Concept

The streets for all concept, which is probably close to the "complete streets" approach, aims at establishing a more balanced use of public space, by promoting active modes of transportation and reducing the prominence of cars (*1*). The main idea is to adapt the streets to their urban context and to make them fit with their expected and real usage. Indeed, these urban roads are more than lanes for traffic, and they should not be exclusively designed or managed for traffic.

Reintegrating walking and cycling as a means of transportation is one of the main goals of this approach to designing streets, whereas the focus has long been solely on the needs of car users. In the meantime, the idea is also to promote mixed-use traffic on streets instead of dividing streets between users. Moreover, this approach complements and is coherent with French law in regard to accessibility for disabled people, which requires a fully accessible public space. This contributes to livable and well-shared streets, which benefits everybody.

Street Use Code and Traffic Calming Areas

One main tool to create this change in attitude and practices is an important evolution of the French "road rules" through the street use code process. Launched in 2006, this new direction was nearly achieved 2 years later with the publication of Decree 2008-754 on July 30, 2008, which modified the existing road rules (*2*).

The main measure was the introduction of "pedestrian priority zones" complementary to "pedestrian area," while the status of the latter was redefined. With the 30-km/h zone, these two types of pedestrian zones constitute what are called "traffic calmed areas," which correspond to parts of towns in which local life is at least as significant as traffic.

According to the updated rules of the Road Code (*3*):

- Motorized vehicle traffic should strongly be limited to accessing specific places within pedestrian areas; speed limits match with the average walking speed, and parking is not possible. Other users must yield priority to pedestrians everywhere in these zones.
- Traffic is not particularly limited in pedestrian priority zones, which are shared zones between all users without any segregation (the literal translation of this French naming is "meeting zone"); the speed limit is 20 km/h, and parking may be allowed in some places, while priority rules are the same as in pedestrian areas.
- Cyclists are allowed to ride into pedestrian areas and pedestrian priority zones, but they have to respect the rules of the road and keep an appropriate speed.

Beyond the regulation context, the aim is to limit motorized vehicles' access to these pedestrian zones to service vehicles and to ban transit traffic. Public transport vehicles may be considered as participating in serving pedestrian zones, particularly when stops are located in them.

During recent years, many more pedestrian areas and pedestrian priority zones have been implemented in city centers, especially in big towns. The medium-term objective is to convert most parts of city centers into such zones, and more globally, a large part of urban spaces into traffic calmed areas. See Figure 1 for a synthesis of running conditions.

Status of the zone or road	pedestrian area	pedestrian-priority zone	30 zone	urban area	70 section
Speed limit	*Walking pace*	*20 km/h*	*30 km/h*	*50 km/h*	*70 km/h*
Balance between local life / traffic function	Traffic / Local life	Traffic / Local life	Local life / Traffic	Local life / Traffic	Local life / Traffic
% of the road network desired in the long term	*0 % - 10 %*	*2 % - 15 %*	*60 % - 90 %*	*10 % - 40 %*	*0 % - 5 %*

FIGURE 1 Synthesis of running conditions in towns.

Renewal of French Tramways

In the meantime, the renewal of tramways has been taking place for several years, both through the extension of existing networks and the implementation of first lines in other cities. At the beginning of 2015, 26 towns and cities, including Paris, had a tramway network comprising a total of 62 lines and more than 1,300 vehicles in operation (Figure 2).

All these tramlines are structuring parts of public transport (networks in these cities). Tramlines are most often designed in a radial way, going into city centers and connecting main zones (universities, hospitals, service activities, and residential areas).

WHY MAKE TRAMWAYS CROSS PEDESTRIAN AREAS?

The conjunction of the implementation of pedestrian zones and the radial structure of public transport networks naturally leads to tramlines crossing significant pedestrian areas in many, if not all, French light rail transit networks. However, further analysis allows for considering several deeper causes of this situation.

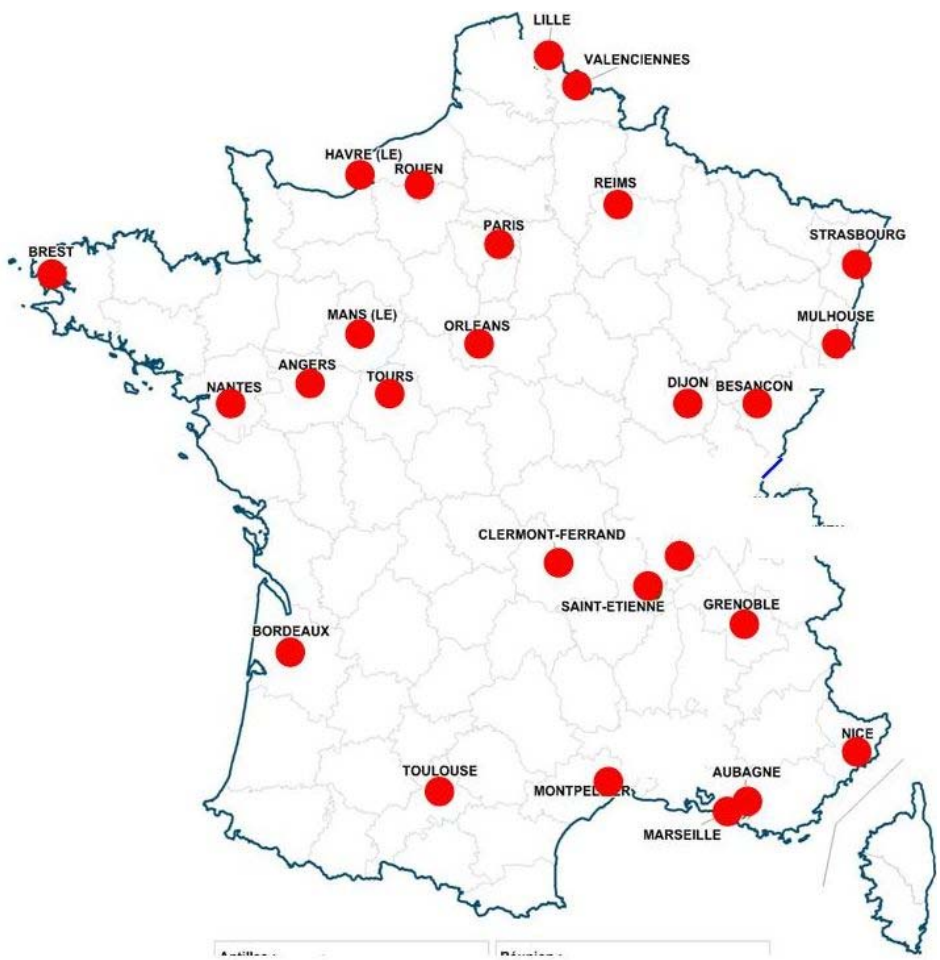

FIGURE 2 Tramway systems in France, 2015.

The first reason is linked with this radial form of networks and the wish to go as close as possible to attractive zones located downtown; the tracks have to be put closer to shopping areas and high-density housing. This leads to making tramlines extend to existing pedestrian areas whose status cannot be changed unless car moderation is no longer desirable. In the case of new projects, a core question is therefore to choose between crossing straight into downtown districts with intense local life or skirting around them on wider streets dedicated to traffic. See Figure 3 for an example of a tramline going into the heart of a city.

In the second configuration, easier running conditions (segregated tracks, full right of way, higher speed) may not balance the impact of lengthening of lines on the level of service. In the meantime, the wishes of residents and shoppers of the central zones have to be taken into account, which is often a challenge, because opinions are divided on the advantages and constraints of having the tramway right at their doors. Studies have shown that inserting a public transport system into commercial zones of city centers would accelerate ongoing trends in terms of activities rather than lead to change. Getting the tramway to go near emblematic places or monuments in historic downtown districts may also be a choice at times for decision makers.

Traffic calmed areas are sometimes extended into hearts of towns where tramway lines already exist. Keeping the original status of the affected streets constitutes a physical break in these zones, while diverting the tracks is generally neither acceptable nor relevant for transportation needs; the solution is therefore to change the status of the affected streets while removing car traffic. Then, inserting tramway tracks into pedestrian zones matches with the mobility needs in these areas (Figure 4).

However, inserting streetcars into narrow streets may lead to the decision to totally remove cars from the street. More than being just a mobility tool designed to provide a high level

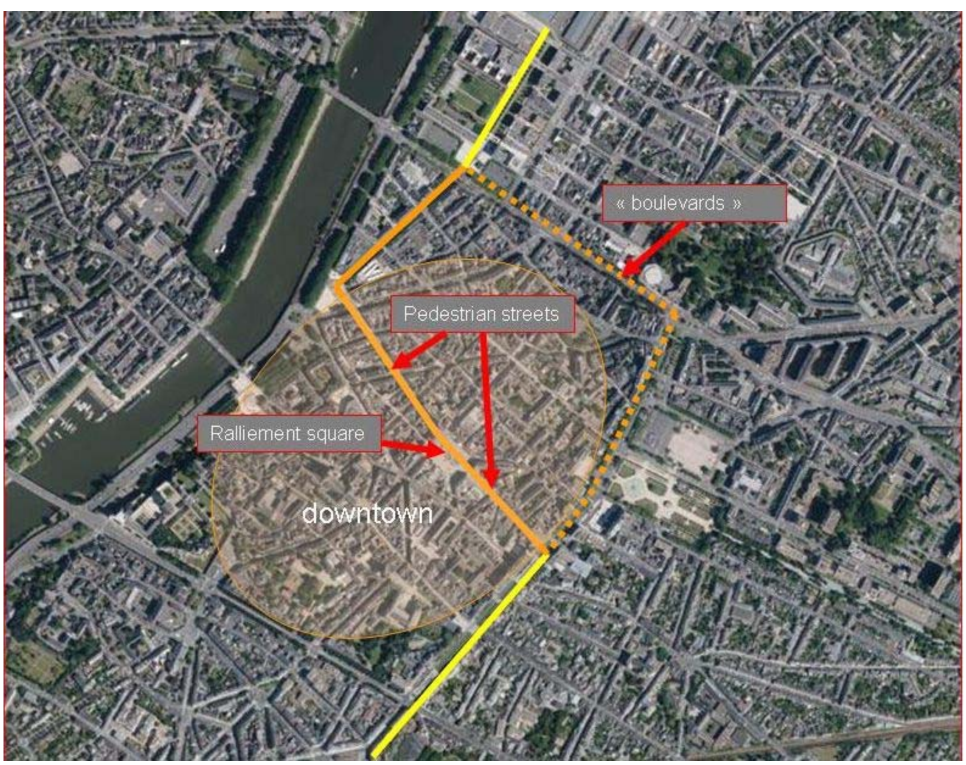

FIGURE 3 A public transport system going straight into the heart of the city, Angers.

FIGURE 4 Car traffic preserved to the detriment of pedestrians, Lyon.

of service, the French "new tram" is well-known for its contribution to the renewal of public space and aims at increasing the quality of local life.

The reduction of the car's place in urban areas is one of the essential principles of using streetcars, while this is not necessarily the case for metro systems. In the case of some narrow streets on which obviously all functions cannot be kept, the creation of pedestrian areas finally appears more and more like an acceptable solution to insert streetcars. It would be preferable to design all elements—platforms, car lanes, tram tracks bed—with the minimum width. Such compromise solutions were in vogue before the streets for all concept was embraced.

REQUIREMENTS FOR STREETCAR RUNNING IN PEDESTRIAN ZONES

Regulation Context: Tramways and Road Rules

As a rail vehicle, tramways do not have to respect general rules of the French road rules. This has two main positive impacts on the interface between streetcars and pedestrians:

- The tramway does not have to yield priority to pedestrians crossing streets or walking in pedestrian areas as do other vehicles.
- In the meantime, pedestrians, and other users, have to get out of the tramway lanes when a rail vehicle is coming, and all users should give trams priority.

However, pure pedestrian areas are preferable to pedestrian priority zones in which the car traffic may remain important enough to disturb tramway operation. In any case, the regulation status of the affected streets is not a self-sufficient solution and must not be decided a priori but rather be a consequence of the technical and operational measures implemented.

Adaptation of the Layouts

Recommendations on the way to design pedestrian zones had been laid out by Certu in November 2008 (*3*). These zones have to be adapted to the presence of tramways in such areas.

Normally, pedestrian areas are totally dedicated to pedestrians, and no identification of accessible places for vehicles has to be made, except for deliveries. This cannot apply to pedestrian areas with tramways where people have to be encouraged to walk out of the gauge limits of streetcars (named GLO in France). At least, pedestrians need to easily get out of the GLO, so no strong separating device should exist if it may be an obstacle. See Figure 5.

Avoiding having people on the tracks also requires providing comfortable walking facilities out of the gauge limits, by keeping a sufficient width and removing obstacles such as urban furniture. Wire-free systems (ground level power supply, batteries, supercapacitors) may be an interesting option to avoid poles, even if hanging catenaries on building fronts is often possible in downtown streets. However, the implementation of an irregular surface inside the gauge limits can make it less comfortable for pedestrians and cyclists.

In addition, there is a need for clear materialization of these gauge limits for all users and especially disabled people (*4*). This must be implemented both on its sides and on its whole surface. The choice of materials and great attention to implementation are crucial, but not easy to achieve. For instance, a little vertical gap to show those limits is appreciated by blind people, while wheelchair users prefer a totally plane surface. See Figure 6.

A general principle is therefore to avoid obstacles on pedestrian areas with tramways. However, barriers would sometimes be useful to channel pedestrians in some particular cases such as gates of malls, metro, or railway stations. Great attention must then be paid to their disposal to prevent people from being caught between streetcars, and to their height, to prevent visibility issues (*5*).

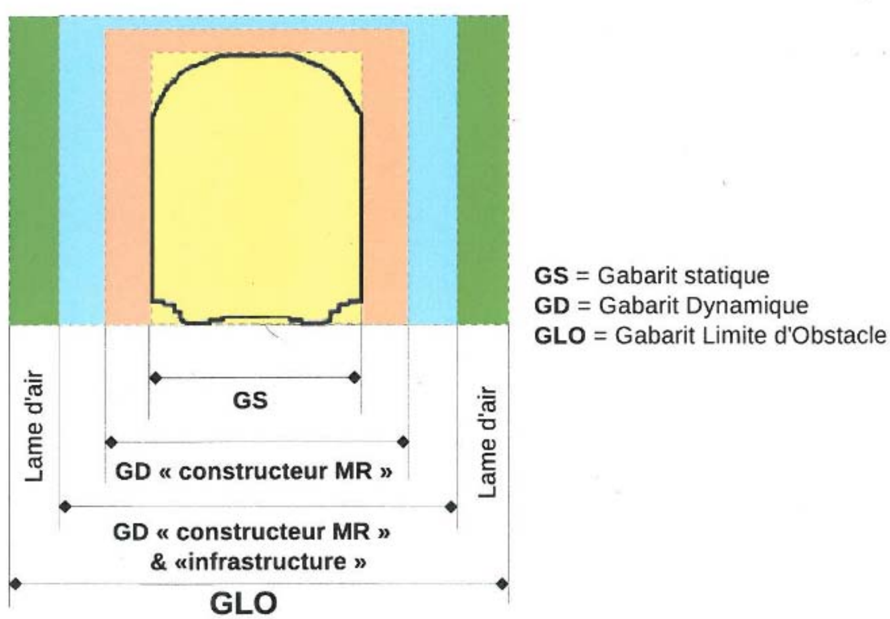

FIGURE 5 Definition of gauge limits.

FIGURE 6 Materialization of the gauge limit, Grenoble.

Adapting Operating Conditions and Ways

Operators also have to adapt their practices to the context of pedestrian zones in which the maximum speed is necessarily lower than on other parts of the network, in coherence with the "drive on sight" principle. However, tramway drivers must keep a permanent and deep concentration all along their route in such areas. Even if the risk of being surprised by users coming out suddenly from secant streets is less important than in normal roads, this is one reason to limit the length of these kinds of layouts.

Right-of-way and efficient priority management on sections of lines out of these zones are required to balance the speed reduction inside them at the scale of whole lines. As long as the length of tracks affected by pedestrian zones is not too long, the impact on level of service normally remains acceptable. However, regularity and commercial speed could be locally affected. Well-protected exclusive tracks and an effective priority at junctions are then desirable on nearby sections to balance this effect at the scale of the whole line.

In some particularly narrow streets (around 10 yd), a solution to keep enough space for pedestrians is to implement single tracks. Two options are available, depending on the context:

- The line can be operated in one way while the return route is organized on a parallel street, but this is not always possible.
- An alternate running of streetcars may be set up for both directions on single tracks. Implementing tracks on two streets is more expensive, but alternate running in one unique street is more complex and constitutes a fragility point for the operation of the whole system (Figure 7).

FIGURE 7 Alternate running on single tracks, Roë Street, Angers.

A particular case is the presence of junctions of tramway lines inside pedestrian areas. Crossing between tracks normally requires rail signaling and heavy procedures to avoid crashes between rolling stocks and leads to streetcars stopping and waiting for open signals.

Lower speed and good visibility between drivers allow setting up simplified maneuvers zones to make this function less complicated and to minimize stoppings of streetcars, thereby aiming at more fluent driving (Figure 8). It has indeed been observed that the less a streetcar stops, the easier it can pass through pedestrian flows.

FIGURE 8 Simplified maneuvers zone, St. Roch Station, Montpellier.

Traffic Management In and Around Pedestrian Zones

In any case, the effective restriction of car traffic in these zones is imperative to achieve a satisfying situation, both for active modes (pedestrians, cyclists) and tramway operators and passengers.This may lead to implementing some access control devices to prevent cars from entering pedestrian areas. But such tools often lead to maintenance issues, and they may also not be very convenient for pedestrians, especially disabled people. A core issue is the maintaining of delivery access, which needs to provide dedicated areas and to set up control.

Traffic management around pedestrian zones is at least as important as this control at delivery entrances; it aims at providing attractive routes for transit, deterring unexpected users from reaching these areas, and achieving good running conditions for tramways, with effective priority at junctions and right-of-way on dedicated lanes.

Traffic handling must therefore be planned on a wide enough scale around the pedestrian zone. In some cases, this may lead to so little car traffic in streets run by tramways that a pedestrian priority zone can be reached de facto, without setting up the corresponding regulations.

Advantages and Limits

Compared with the bus, streetcars have a good image, which may make it easier for pedestrians to accept them: they are less noisy and polluting, and they also appear to be more "soft" and friendly despite their inferior braking performances, larger size, and the presence of rails. The customized design of French tramways for each town, the smooth way they run, and the comfort they give to passengers probably contribute to that positive image. As for bicyclists, their behavior is often moderated by pedestrians in such zones in that they must share the space with them, and their behavior is then less erratic around the tramway than in other places.

Generally, streetcars and pedestrians coexist well in pedestrian environments, because streetcars operate smoothly at moderate speeds. Drivers do not use warning devices any more than in nonpedestrian areas. There are few significant safety issues for tramways in pedestrian zones as indicated by the low number and severity of tram–pedestrian accidents.

The upper limit of tramway acceptance in pedestrian areas is probably related to streetcar frequency. When several lines share the tracks, the large number of streetcars can create a wall in the middle of the street. This is not acceptable because it can have negative safety impacts caused by risky pedestrian behavior. With respect to operations, this may affect the level of service while restricting access to stops.

RELEVANT PLACES FOR INSERTION OF STREETCARS INTO PEDESTRIAN ZONES

Major Historical Roads Crossing Commercial and Service Districts

Major streets are generally wide enough to insert tramway lines in good conditions, while keeping enough space for local activities and pedestrians (Figure 9). Such streets provide interesting straight routes through downtown districts and quick access to shops or offices, so the main issue is access control to prevent cars from going into these zones. Managing deliveries may also be difficult to achieve to prevent deliveries from disturbing tramway operation or impeding pedestrian paths.

FIGURE 9 Streetcar in a commercial big avenue, Reims.

Forecourts of Railway Stations

Central railway stations generally are key points of tramway networks, to connect passengers to suburbs or other towns. As these stations are also places of choice to implement a pedestrian area, because of the importance of generated flows it is obviously logical to find opportunities or necessity to let tramways circulate into such pedestrian zones (Figure 10).

Multimodal Connection Centers

The situation is quite the same as near railway stations; however, the status of pedestrian areas may not be so obvious or easy to achieve because of the presence of many buses and coach lanes. This often contributes to a "road climate," and the management of conflicts between streetcars and vehicles makes the situation complex for pedestrians and cyclists (Figure 11).

Plazas

In such places, pedestrian areas often may be set up by totally removing motorized traffic or at least moving car lanes around or on one side of the plaza. For various reasons, particularly geometric issues, tramway tracks often go straight through the square (Figure 12). The main issue may then be the loss of landmarks for pedestrians, especially for blind and partially sighted people. However, plazas often provide opportunities for architectural acts and artistic urban furniture, and great attention is to be paid to potential visibility issues related to those elements. See Figure 12.

FIGURE 10 Streetcar on a railway station forecourt, Montpellier.

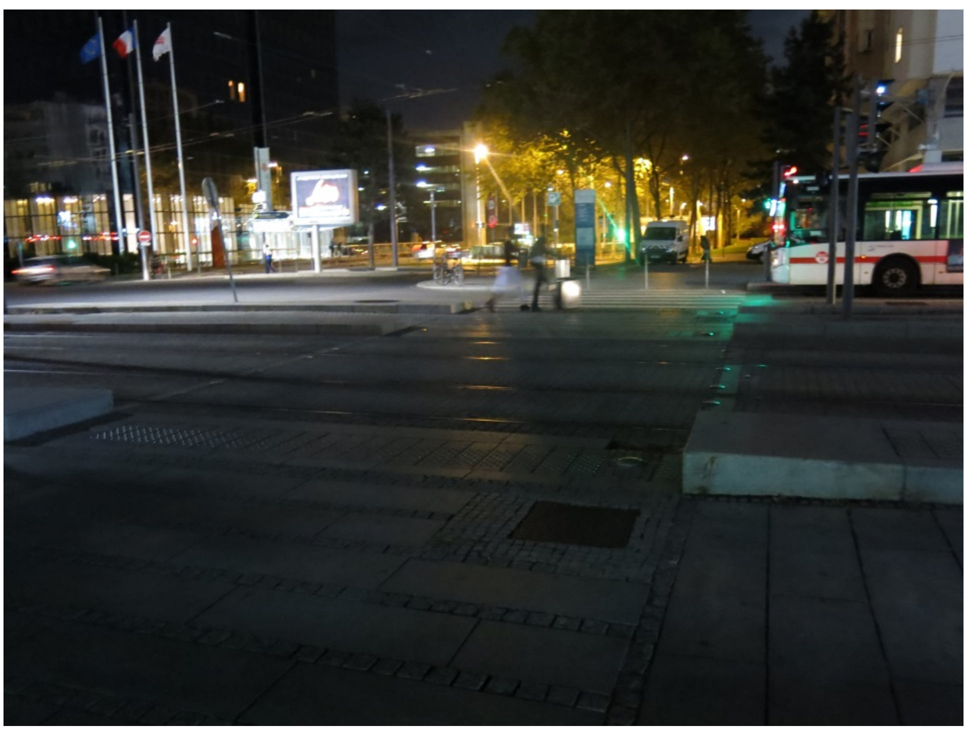

FIGURE 11 Public transport connection center, Part Dieu, Lyon.

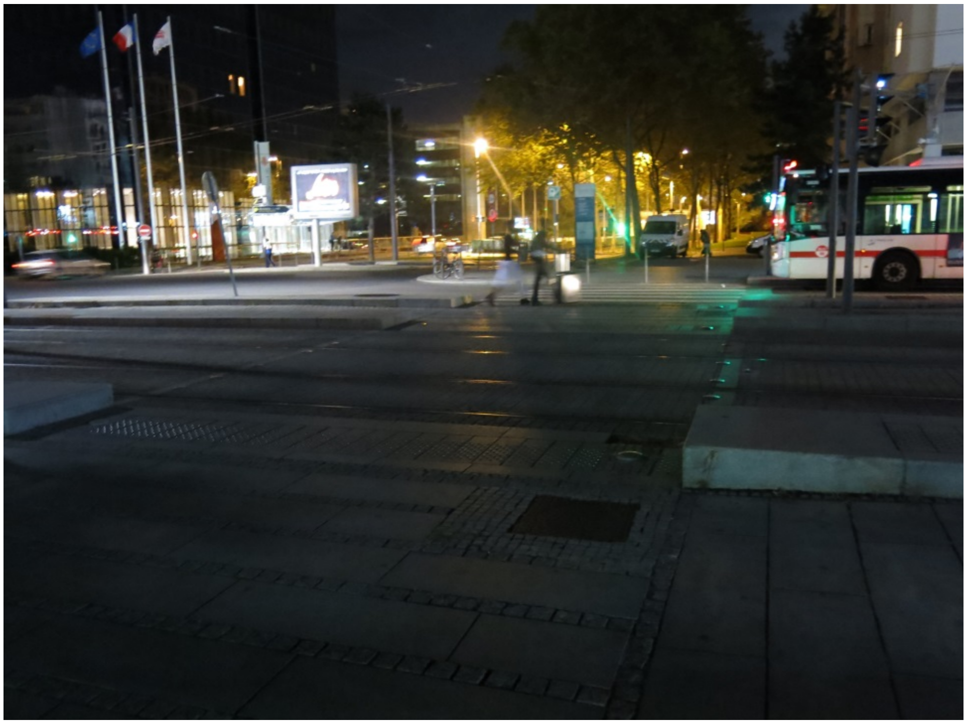

FIGURE 12 Streetcar crossing a plaza, Massena Square, Nice.

Narrow Streets

Insertion of tracks into narrow streets generally results from the wish to let tramways reach the heart of city centers or emblematic places despite technical challenges and impact on service level. Sometimes the need for accessibility by car for inhabitants or any other sufficient reason to keep motorized car traffic may be strong enough to put the tramway into mixed traffic or to implement a pedestrian priority zone. However, in many cases, this can be solved by removing car traffic and implementing a pedestrian area (Figure 13).

Lateral Location of Tracks in Wide Streets

This particular situation may be complex in regard to regulations in that it requires a different status for two parts of one street, and the distinction between them must be clear. When the tram tracks are close to the car lanes, it is not feasible to allow people to walk or cross through the tracks along the street. Furthermore, it could be dangerous to encourage such practices because of the close presence of car lanes. When the tracks are parallel to pedestrian and auto areas, as shown in Figure 14, a dissuasive separator is suggested.

FIGURE 13 Streetcar tracks in a narrow street, National Street, Tours.

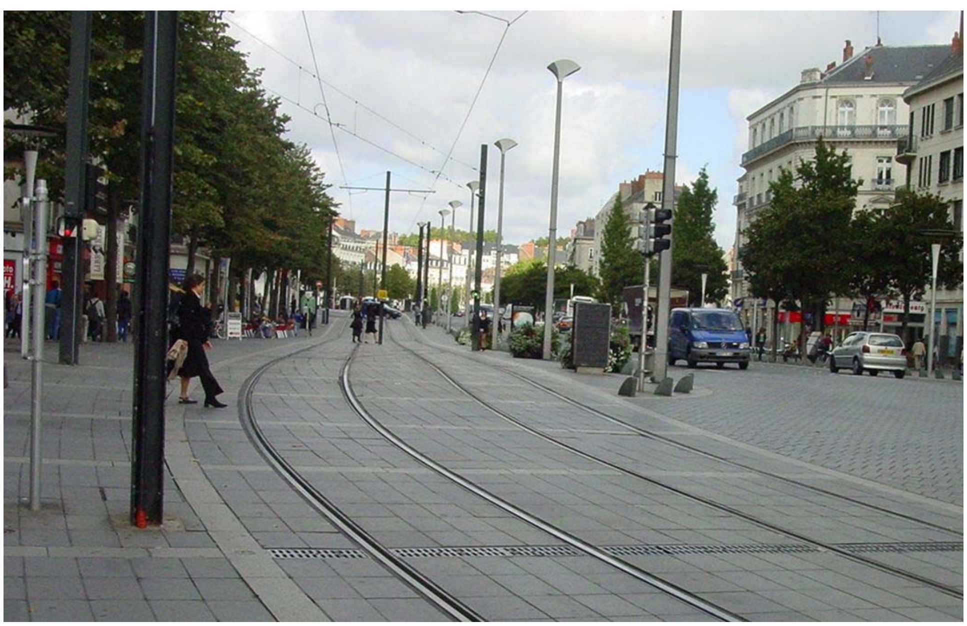

FIGURE 14 Lateral tracks along a wide platform, Nantes.

CONCLUSION

In France, more and more tramway lines are going through pedestrian zones because of the ongoing development of this public transport mode and the increasing number of pedestrian zones in city centers. After some years of operation, it can be concluded that the insertion of streetcars into pedestrian areas does not lead to critical safety issues, while the impact on commercial speed or regularity generally stays acceptable, as long as precautions and adapted measures have been implemented.

Observation of various examples may help to highlight some key facts of such success stories:

- A strong management of car traffic in and around pedestrian areas is compulsory to avoid disruption of cohabitation between streetcars and pedestrians. Because the impact of pedestrian zones on the level of service at the line scale must stay limited, this requires both limiting the number and the length of track sections in such areas and balancing their influence by good conditions on the rest of the line.
- Inside pedestrian areas, a clear materialization of gauge limits, some comfortable ways to walk beside tracks, and good conditions of mutual visibility are required; pedestrians must also be able to easily escape from the tracks when a tramway is coming,
- Finally, the good image of streetcars probably has a role in acceptance by pedestrians, as long as streetcar frequency does not lead to making a wall in the street.

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State of the Art in Vehicles

LRT and Streetcars

Ergonomics and Visibility in the Tramway Driver's Cab

ALEXANDRA GUESSET
STRMTG (French Ministry of Transport)

The Service Technique des Remontées Mécaniques et des Transports Guidés (STRMTG) is a department in charge of safety for ropeways and guided public transport for the French Ministry of Transport. The STRMTG's Tramways Department (DTW) edited in 2012 a guidebook on the ergonomics of drivers' cabs in tramways. The guide aims to set minimum standards for designers of rolling stock to ensure an appropriate visibility for drivers and to address the needs of the tramway operators.

The safety of tramway systems is in particular based on line-of-sight driving principles, but no regulation or standard exists for visibility requirements. Therefore, the STRMTG started a process for elaborating a frame of reference to share with concerned professionals.

These specifications focus in particular on the following:

- Visibility: close and far-off outside fields of vision, inside field of vision, area swept by windscreen wipers, and so on;
- Location and type of controls; and
- Windscreen and side windows.

The two driving positions are studied (centered and off centered), and a specific part of the guide deals with tram-trains and their compatibility with conventional railway standards.

Because the field of the STRMTG is exclusively safety, in 2015 the original guide was divided into two parts: the STRMTG guide concerns safety prescriptions, and a second guide deals with comfort specifications. The second guide was coedited by the UTP (union of French operators in public transport) and the GART (union of French public authorities in charge of transport policy).

This revision of the guide also aimed to connect public authorities in charge of transport policy to the design process because they are decision makers in the choice of the rolling stock design. These guidebooks should be part of contract specifications.

MAIN OBJECTIVES

To elaborate a reference on driving-cab design, the DTW created a working group of operators, manufacturers, and an ergonomics specialist. The latter was in charge of the first step of the process: retrieving observations from drivers and questionnaires in seven tramway networks. A proposition of specifications was based on these observations, on European regulations and standards for road vehicles (especially buses that operate in the same urban environment), and on standards for conventional railway rolling stock (French and European standards).

After debate with the working group, specifications were defined for anthropometrics data to characterize drivers' population, visibility, commands location, driving chair, alarm signals, and lighting. The consultation with concerned professions enabled defining specifications that are technically feasible.

In France, public authorities in charge of transport organization tend to use tramway liveries as a visual identity for the city. Consequently, aesthetics designers' requirements have great influence in defining the shape of the tram end. Unfortunately, visibility is not a criterion taken into account. As no frame of reference exists for the tram driving cab, the operators, who are not in charge of buying rolling stock, are helpless in the face of aesthetics designer decisions.

Operators share the same needs on several items, such as visibility or comfort, and they would have more influence if their requirements were determined. At the same time, the DTW wanted to have precise specifications to ensure an adequate visibility for drivers, particularly in response to two severe collisions with pedestrians who were hidden by pillars (one fatality and one serious injury).

For these reasons a guidebook on the tram driving cab was created.

EUROPEAN REQUIREMENTS ON OUTSIDE FIELD OF VISION

The method to define the requirements could not be based on the following European references because it appears that these standards define main objectives only for visibility:

- *Recommendation of Type: Light Rail Vehicles*, edited by VDV (German Association of Public Transport Authorities). requires that windscreens and side windows "offer good sight."
- The *Ordinance on the Construction and Operation of Street Railways* (German federal regulation known as BOStrab) specifies that the cab "must be so designed that the driver may carry out his duties safely. In particular he must be provided with an ample field of vision."
- The federal Swiss office (OFT/BAV) specifies in *Measures of Execution of Railway Regulation* that there should be "measures guaranteeing good visibility with windows sufficiently large."
- *Guidance on Tramways*, edited by the ORR (Office Railway Regulation of the United Kingdom), refers to the current Road Vehicles Regulations 1996 (similar to the European Community directive) for a tram that operates on the street and specifies that "the design of the driver's cab should offer optimum internal and external visibility for the driver."

Therefore, specifications are defined here to prevent collision scenarios and address on-road vehicle regulations.

DRIVERS' OPINIONS

To determine operators' needs, the ergonomics specialist studied seven tramway networks (in Rouen, Marseille, Montpellier, Lyon, Grenoble, Strasbourg, and Clermont-Ferrand) with various rolling stock types made by Alstom, Bombardier, and New Translohr (tramway on tires) (*1*).

The observations highlighted that most drivers were unsatisfied with the driving chair quality and that some had trouble in reaching or activating the pedals. It also showed the problem of driver's desk and screen reflections on the windscreen, of mist on side windows, and of sunshields not being effective enough. Drivers asked for an improvement in the visibility toward the bottom area close to the tramway end (risk of not seeing a child walking ahead) and behind the pillars. (See Figure 1 and comparison of the old and new designs in the sections on Practical Application: Aubagne's Rolling Stock and Tram-Trains.)

When drivers were asked to list which dangers they focus on while driving, they first answered pedestrians, especially children; then mixed-traffic areas (road vehicles on tram track); cyclists; and last, the entrance in the tram stop.

DRIVERS' POPULATION AND POSTURE

The first step was to define anthropometrics data to characterize the drivers' population in order to design the driving cab around the driver's posture. A European standard for safety of machinery (2010 version) was chosen instead of the European railway standard, which had a taller population, because operators are trying to increase female representation in the drivers' profession.

Three dummies are defined: 5th, 50th, and 95th percentiles [stature with shoes on, respectively, of 1,560 mm (61 27/64 in.), 1,749 mm (68 55/64 in.), and 1,911 mm (75 15/64 in.)]. The 50th percentile takes into account that drivers are not static during their working time. Each dummy's length is defined, and one point stands for the middle of the eyes. A table defines the acceptable angles for the main articulations; those values concern biomechanical constraints and comfort angles.

Each requirement has to be checked with every dummy. The driving position is defined as a dummy having its back in contact with the seat back at an angle of 5° to 10° toward the rear. The shock absorber is at a mean value (otherwise impact on the height).

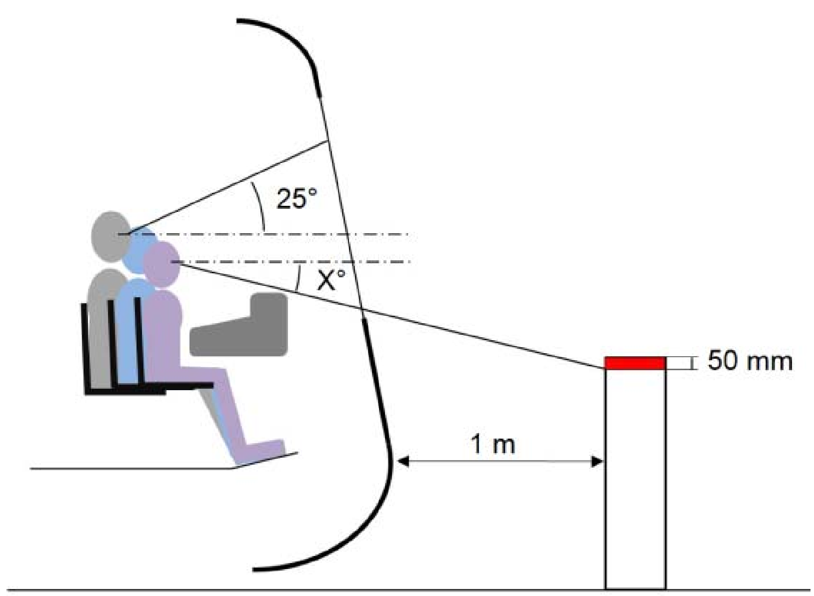

FIGURE 1 X° definition.

REQUIREMENTS FOR VISIBILITY

The safety guidebook mainly focuses on visibility for several reasons: the line-of-sight principle, which is fundamental in tramway safety, and a specific visual strategy in getting information in tramway driving. This strategy is close to the one used in bus driving (same urban environment); however, it is more demanding and stressful. Indeed, because of a longer stopping distance and the impossibility to avoid obstacles, a tram driver has to anticipate more than does a bus driver. Drivers mainly use far-off vision when they detect no close obstacle and proceed to regularly look over both sides in a closer field of vision.

Ensuring good visibility from the cab allows drivers to anticipate conflicts with pedestrians or cars and adjust speed in advance, rather than brake sharply (275 victims in 2012 in France). To address the dangers drivers are most afraid of, requirements were defined to improve driver ability to see pedestrians and cyclists. When a requirement about visibility is defined, it is implicit that the driver has direct visibility (no use of onboard camera or mirrors for example).

Far-Off Outside Field of Vision

This field of vision is important for drivers so that they can anticipate when the tramway is moving and see the tram signals clearly. The windscreen covers up to at least 25° above the horizontal plane (in the profile plane) located at eye level for every dummy in the test. As in the European Community directive about road vehicles, the forward field of vision shall cover at least 180°.

There shall be no obstacle, especially pillars, in an angle of 100° minimum (90° allowed), called β, symmetrical about the tram axis. This requirement enables drivers to see a car stopped at a traffic light when the platform is sidelong inserted (embedded track plus road lanes are wide of 24 m) until 20 m before the tram traffic light (20 m refer to the stopping distance in emergency braking at 30 km/h, the usual speed instructions to cross a crossroads).

The angle of obstruction, called α, of each pillar or any other equipment shall not exceed 6° (6.5° allowed) on the range from 25° above the horizontal at eye level to X° below the horizontal. X° is defined as the angle at which the driver can see the upper 50 mm (1 31/32 in.) of a cylinder of 300-mm (11 13/16 in.) diameter and 1,100-mm (43 5/16 in.) height located at 1 m (39 3/8 in.) in front of the foremost surface of the tram. This requirement covers the risk of obstructing the view of a pedestrian or a cyclist while the tramway is moving. In 2010, two severe collisions with pedestrians were blamed on the wide pillars (angles of obstruction of 8° and 18°).

In case of the off-center driving position, an additional requirement defines an angle of no obstruction of 25° minimum above the line of sight. The aim is to prevent a pillar from being too close to the driver. (See Figure 2 for angle requirements.)

Close Outside Field of Vision

The close field of vision is particularly important when the tram is restarting. The goal is to limit hidden areas so the driver can detect a danger and easily see the tram lights. Managing the tram start is especially important in areas with lots of pedestrians—at tram stops, for example. The main risk to avoid is a collision with pedestrians. A child 6 years old is defined in the United Nations' *Global Technical Regulation No. 9 Regarding Pedestrian Safety* as the age when a

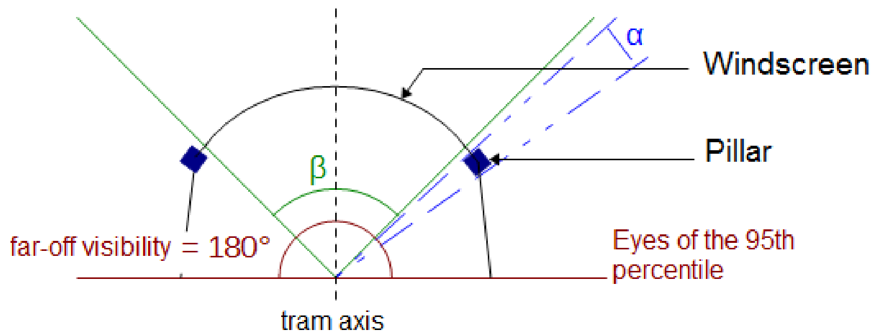

FIGURE 2 Far-off vision angle requirements.

child is considered autonomous when moving. Some debates occurred on the stature of the child: an 1,100-mm (43 5/16 in.) stature was finally maintained because an International Organization for Standardization standard applying to bus vehicles has a requirement of visibility on a bar placed at a height of 1,100 mm (43 5/16 in.). [The French textile industry considers that a 6-year-old child is 1,100 mm (43 5/16 in.) up to 1,160 mm (45 43/64 in.) tall.]

A cylinder of 300-mm (11 13/16 in.) diameter and 1,100-mm (43 5/16 in.) height stands for a 6-year-old child. It is located in the 180° forward field of vision at 1 m (39 3/8 in.) in front of the foremost surface of the tram (Figure 3).

The former version of the guidebook had a general objective about the driver's capacity to detect this cylinder. A general objective could allow that, if the visible percentage of the cylinder surface is strictly superior to zero, then the requirement is fulfilled. Therefore, work was done to define an impartial criterion of visibility. The values were determined from different layouts of existing rolling stocks.

The driver shall see the cylinder

- In case of a pillar obstruction, at least 4% of its reference surface. This reference surface is defined as the sum of the projections of the top and the front surfaces. The projection plane is orthogonal to the driver's line of sight and located at the point located at 1 m in front of the foremost surface of the tram on the top surface of the cylinder. It is allowed to sum discontinuous visible surfaces to reach the 4% goal (Figure 4).
- In other obstructions, at least the upper 50 mm (1 31/32 in.) (Figure 1).

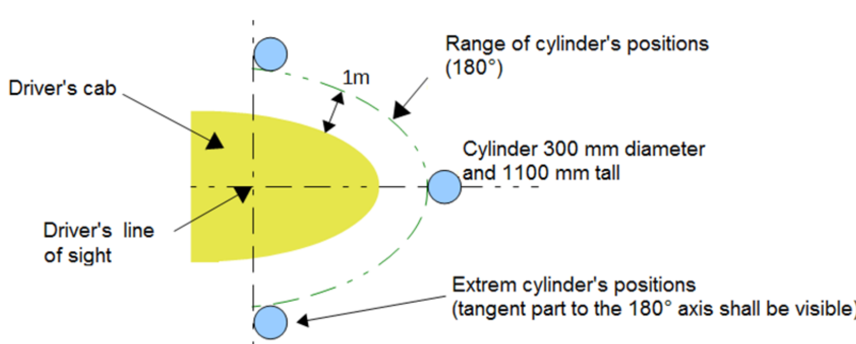

FIGURE 3 Positions for visibility requirements on cylinder.

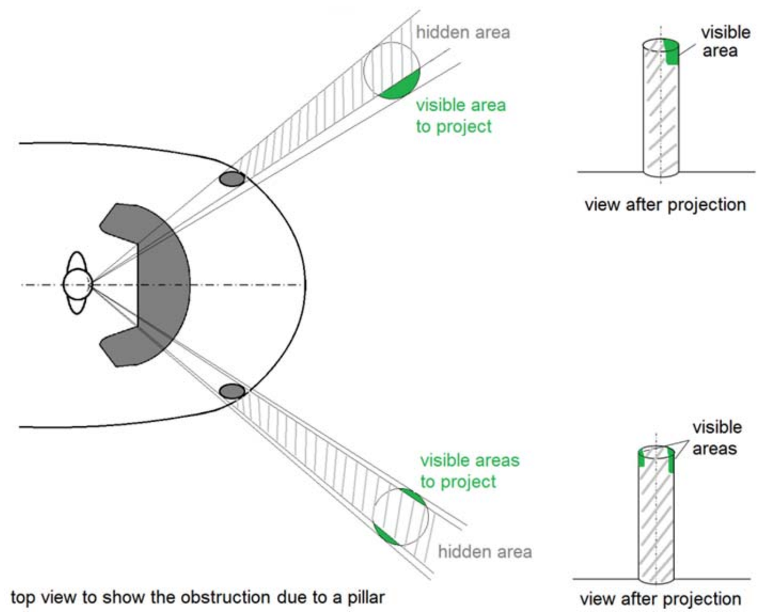

FIGURE 4 Projection planes.

Monitoring of Passenger Turnaround

To address one of the dangers drivers fear the most, specifications about the function of monitoring passenger turnaround were defined. The 2015 version of the guidebook distinguishes the function from the equipment usually used to fulfill this function, that is, the rearview camera. This camera is indeed used for two functions: the aforementioned one and the monitoring of tram sides while the tramway is moving. A survey in French networks was done about the benefits and inconveniences for this second use. The rearview camera helps drivers particularly in mixed traffic (road vehicles on embedded track), but in some collisions, drivers claimed their attention was focused on a vehicle overtaking the tram so that they did not see the third party forward. As this survey did not did not lead to a conclusion in one way or another, this use while the tram is moving is not a safety function.

The monitoring of passenger turnaround covers two risks: tram trapping passengers between the doors and tram dragging passengers. When at a tram stop (straight track) the monitoring device must be able to detect a cylinder 1,100 mm (43 5/16 in.) tall on the whole door width (door open).

The need to see the whole width is a new requirement introduced in the 2015 version of the guide (cylinder at door's axis in the previous version, ends of the doorway not included) at the request of operators who, on one hand, have an increasing number of children traveling alone and, on the other hand, have to ask passengers to step aside to let people get out. This new requirement covers a frequently occurring situation but is demanding for some manufacturers to supply, especially to enable seeing the end doors (close to the rearview camera).

The cylinder is at 50 mm (1 31/32 in.) at most from the doorstep. This device shall be activated as long as part of the tram is still in the tram stop. (See Figure 5 for turnaround specifications.)

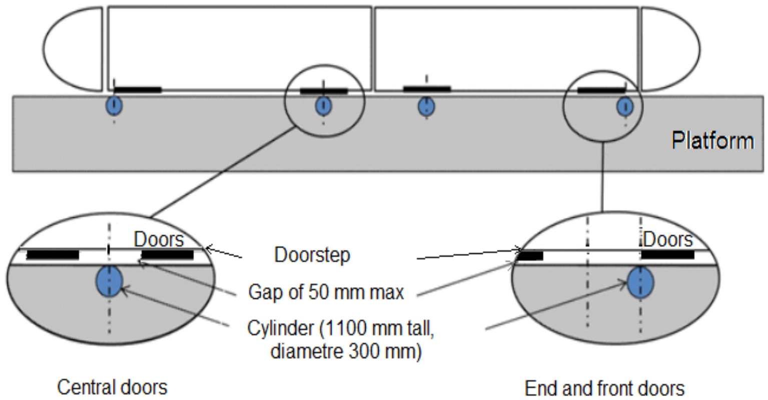

FIGURE 5 Monitoring passenger turnaround.

Some specifications are defined in case the monitoring device is a rearview camera (resolution, contrast, lightness, and arrangement of pictures consistent with reality).

The previous specifications about screen size were removed because the size should depend mostly on the position of the driver relative to the screens. The requirement to have a color camera was also removed because some operators prefer black and white cameras for a better contrast.

CONSEQUENCES OF POSTURAL CONSTRAINTS

Both the safety and ergonomics guidebooks deal with the theme of this chapter on several levels.

Driving Chair

Operators asked to keep some requirements in the safety guidebook about minimal sizes: seat width and depth, back width and height, seatback adjustment, and seat adjustment to the horizontal. The ergonomics guidebook completes these specifications with recommended sizes and other features (width of the lumbar back part and headrest width and height). It also recommends consulting an ergonomics specialist for the driving chair, which is a key device for drivers.

The ergonomics guidebook defines a maximum time of 1 min for the main adjustments of the driving chair. It also defines comfort recommendations to filter vibrations and the possibility to rest forearms on flat and adapted surfaces.

Footrest When Driving with a Master Controller Handle

The safety guidebook defines requirements for foot-operated controls if need be (for example, gong or driver's activity control actuator). All dummies in the study can activate those controls in respect of the table of articulations angles.

A space shall exist to rest the foot for every dummy (specially the 5th percentile), and there is enough space between controls so one foot cannot activate both controls simultaneously to avoid a wrong activation of those controls. The ergonomics guidebook suggests a value of 50 mm (1 31/32 in.) between controls.

The ergonomics guidebook asks for an adjustable footrest because some operators did home improvements so that short drivers can put down their feet. It also defines a force inferior to 40 N and recommends a force of about 25 N.

Traction and Braking Controller Pedals

As traction and brake are controlled by foot, the force to activate these pedals has a safety role: the driver shall be able to dose accurately the traction and brake in order to limit the risk of a passenger falling in the tram or a collision caused by insufficient braking. Ranges of activation force for the traction pedal and for the braking pedal were defined. The surface of the braking pedal has to be nonslip.

To avoid a wrong activation, there shall be enough space between pedals so one foot cannot activate two pedals simultaneously, and a space is required to rest the driver's feet. To be similar to road vehicle driving, acceleration and braking pedals are activated by the right foot, and the braking pedal is on the left of the acceleration pedal.

Master Controller Handle

In case of a driver's sudden weakness, if the driver lets go of the master controller, it shall not stay in a traction position and has to come back at least into neutral position. To avoid unnecessary emergency braking, a notch must exist to distinguish emergency braking from service braking and the neutral position from other positions. As for traction and braking pedals, the forces to activate the master controller are limited, and there shall be a space to rest the driver's forearm.

Inside Field of Vision

While driving, the driver shall be able to see some indicators without losing the vision of outside environment. Four indicators have to be located in the inside field of vision: tachometer, passenger emergency alarm, passenger emergency call alarm, and technical faults alarms.

The inside field of vision is defined in the vertical plane from 20° over the horizontal plane (at eye level) to 30° above (40° allowed) and in the horizontal plane at 50° at most from the line of sight (preferentially 35°) (Figure 6).

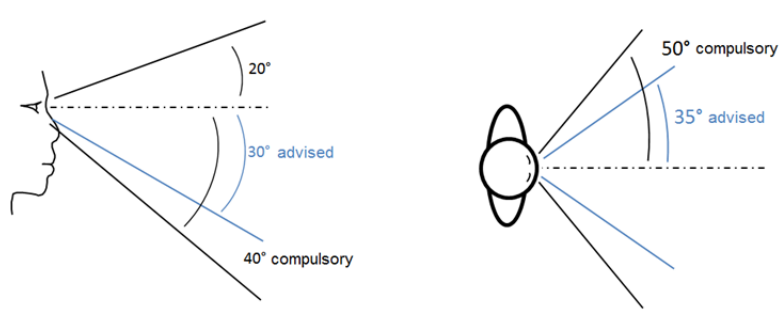

FIGURE 6 Inside field of vision.

The ergonomics guidebook adds a preference for the tachometer position to be horizontally centered and vertically as close as possible to the angle X, defined as the angle at which the driver can see the upper 50 mm (1 31/32 in.) of the cylinder at 1 m (39 3/8 in.) in front of the tram end.

Controls

Some general principles are defined to order controls locations in three areas. Controls shall be located in regard to their impact on safety and their use frequency. For example, two functions potentially used simultaneously do not end up with the driver's arms crossed.

A control is not necessary in the inside field of vision but should be reached intuitively if often used such as a gong (bell), horn, driver's activity control, warnings, and security braking.

A control that is seldom used but has a safety role must be located in an easily reachable area and has to be clearly identified during the day and night.

As in conventional railways, three situations are defined:

1. The driver is in driving position (as defined at the beginning of this document), looking forward, and handling the master controller if need be. Controls in this area have to be reachable with a simple arm movement without any trunk movement from the driving position.
2. The driver sometimes uses a control while driving. In addition to an arm movement to reach the control, the driver can move his trunk up to 15° either bending in the profile or lateral plane.
3. The driver rarely uses a control and may stand up to reach it.

Both guidebooks detail main controls and allocate to each an area of location for the minimum requirement for reachability (if a control is listed in Area 2, it can still be set up in Area 1).

According to the tramline configuration, the safety analysis can result in a higher demanding location than the one defined in the guidebook.

If a control includes several functions, this control shall be located at the most demanding location.

The list of controls was discussed with the working group and is available in both guidebooks. The safety guidebook would list only controls having an impact on safety.

Some controls have to be lead sealed, such as an isolation switch for the bogie, reverse running, and isolation for driver's activity control actuator. (See Figure 7 for controls locations.)

Driver's Activity Control Actuator

This item is an important issue in ergonomics in that drivers repeatedly activate this control all day long. Therefore, the safety guidebook only summarizes the features the actuator shall have to fulfill its role: for example, if the driver loses consciousness, the actuator cannot remain activated if the driver's hand drops on a push button or his leg weighs down a pedal. The working group dealing with the function of the driver's activity control actuator will complete the ergonomics guidebook.

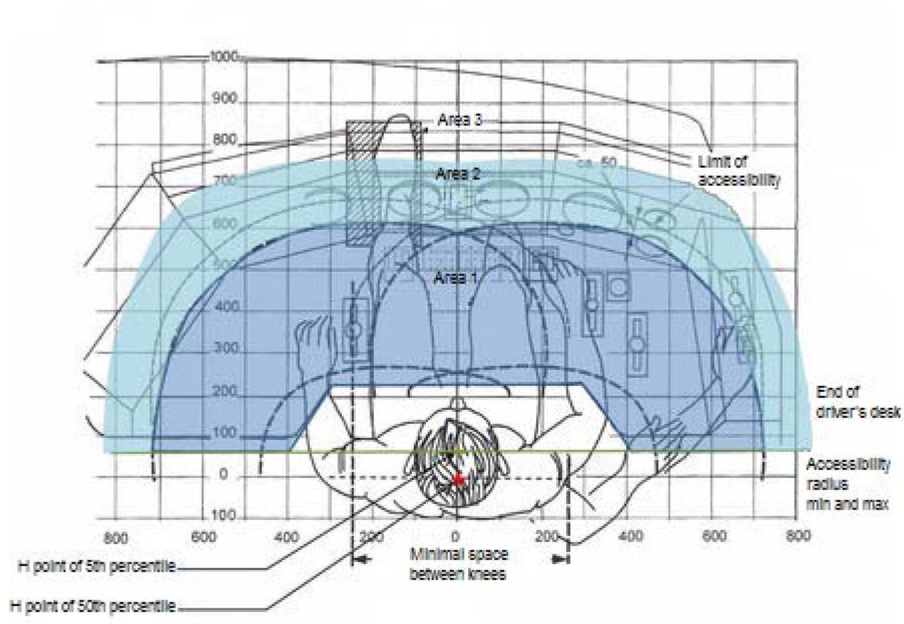

FIGURE 7 Areas for control locations.

In the case of a hand-operated actuator, the force should be around 2 N or at most 3 N. It is recommended that several means of prehension be provided:

- In the case of a hand-operated actuator with repeated activation, the actuator should be completed by one that is foot operated.
- In the case of a hand-operated actuator with continuous activation, upper limb tensing should be avoided. The forearm should be supported on a wide surface, and a support for the hand or wrist is also recommended. The force of activation should be limited: a sensitive device is recommended, or a push button with a force inferior to 3 N is allowed.
- If the hand-operated actuator is not combined with the master controller, it should consist of several actuators, all located in Area 1.
- In the case of a foot-operated actuator with repeated activation, the force of activation should be either inferior to 12.5 N if only the ankle extension is used to move the pedal or inferior to 19 N if the whole leg is used. This kind of activation is incompatible with foot-operated driving. It is recommended to double this actuator with a hand-operated one, whose force of activation would be around 2 N.

The case of a foot-operated actuator with continuous activation is not specified in the guidebooks because there is no existing pedal that can guarantee that only foot or leg weight will not continue to activate the pedal in case of an incapacitated driver. One event occurred in a train in 2003 in Waterfall, Australia, caused by the driver's heart attack: the driver's activity control—a foot-operated actuator with continuous activation—did not detect his failure because his leg weight was enough to keep the pedal activated (the leg was blocked against the wall).

Measurements of Driving Cab

Information on measurements of the driving cab exists only in the ergonomics guidebook. This guide defines a minimum height of the cab; space for arms, legs, and feet; and the absence of any aggressive protuberance on ceiling.

DRIVER’S CAB ENVIRONMENT

Windscreen and Side Windows

The prescriptions of this chapter in the safety guide apply to windscreen and side windows located in the 180° forward field of vision.

A French conventional railway standard in regard to windscreens was partially used for requirements and tests about photometric features (factor of luminous transmission) and vision quality. In addition, it is specified that perception of colors of lights directed at tram drivers or at road vehicle drivers should not be changed, especially in case of a tinted windscreen.

Efficient demist and deicing systems must equip the cab and shall not lead to a visual distortion. The demist system on the windscreen shall cover at least the same area as the windscreen wipers. On side windows, it shall cover at least 80% of the surface for a range of height from 20° over the horizontal plane at eye level to X° above (see Figure 1 for a definition of X°).

Windscreen Wipers

The area swept by windscreen wipers was not satisfactory according to operators so a new area was defined in the safety guidebook:

> In the area over the horizontal plane at eye level, a triangular surface with its summit on the line of sight (or tram axis for the centered driving position) at 20° minimum above the horizontal plane and the other points at least 40° (35° allowed) laterally for both; and
>
> In the area above the same horizontal plane, a surface symmetrical about the tram axis between at least 40° (35° allowed) laterally for both sides and up to X°.

The windscreen wiper field must cover not less than 95% of this area because of the technical difficulties in sweeping both corners as well as a limited bottom centered area. This goal of 95% remains an improvement in comparison with the equipment used in tramways designed before the original guidebook was edited.

Wipers shall have variable speed, and their rest locations shall be outside the windscreen wiper field or on its edges. The wiper width will be limited so that it is not an obstruction to visibility. (See Figure 8 for windscreen wiper specifications.)

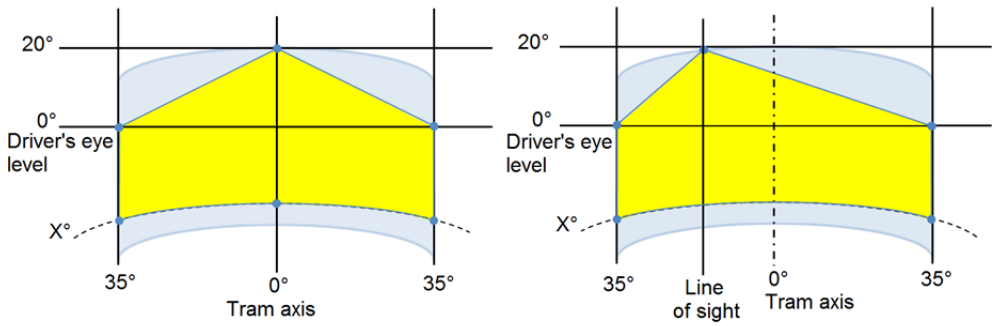

FIGURE 8 Windscreen wiper field.

Sunshield

Driver cabs shall be equipped with a sunshield (tinted window or sun visor, for example) for all windows located in the 180° forward field of vision. The eyes of each dummy in the study were protected against direct sunrays so that drivers are not dazzled.

Alarm Signals and Noise

The safety guidebook defines a minimum level of acoustics pressure above the level of surrounding noise so that safety alarm signals can be heard. The quality of these signals and the coherence between auditory alarm signals and visual signals will respect the requirements of a European standard for safety of machinery (NF EN 981).

Lighting

The passenger area and the cab interior shall not reflect on the windscreen, and the luminous source of cab lighting shall not be in the driver's field of vision.

Cab lighting will respect the specifications of the European standard NF EN 13272 "Electrical lighting for rolling stock in public transport system" (2012 version).

Thermal Comfort

This item is only specified in the ergonomics guidebook. Some operators underlined that a bad orientation of air nozzles and a high air output can create a real discomfort for drivers. The equipment should be adjustable so as to not create discomfort. The air output and temperature in the driver's cab should be independent from those in the passenger area. A system to heat the driver's feet should be installed.

PRACTICAL APPLICATION: AUBAGNE'S ROLLING STOCK

The first rolling stock that complies with the visibility requirement has been running in Aubagne since the end of 2014. The comparison between an old design [a 2.6-m-wide (102 23/64 in.) rolling stock with large pillars] and that of Aubagne's design shows a big improvement in the visibility of two cylinders: one represents a child 1,200 mm (47 1/4 in.) tall (used before the original guidebook), and one is for a child 1,100 mm (43 5/16 in.) tall.

Although the cylinder of 1,100 mm (43 5/16 in.) tall is always visible from the Aubagne cab for both the 5th and 95th percentiles, the pillars in an old design hide completely both cylinders, and the 5th percentile cannot see the 1,100 mm (43 5/16 in.) tall cylinder in the front windscreen (can see only in the side window). (See Figure 9.)

TRAM-TRAINS

The 2015 version of the safety guidebook also deals with tram-train cabs. As tram-trains can operate in the same urban environment as tramways, they share the same needs. But because there are more regulations in conventional railways and more controls in the driving desk, compatibility with the tram specifications was analyzed.

Six points were adapted: dummies, maximal obstruction angle caused by a pillar, tolerance for having an indirect visibility on the cylinder, definition of vertical plane for the inside field of vision, location of controls, and the windscreen wiper field. (See Figure 10 for a pictorial view of the old and new designs.)

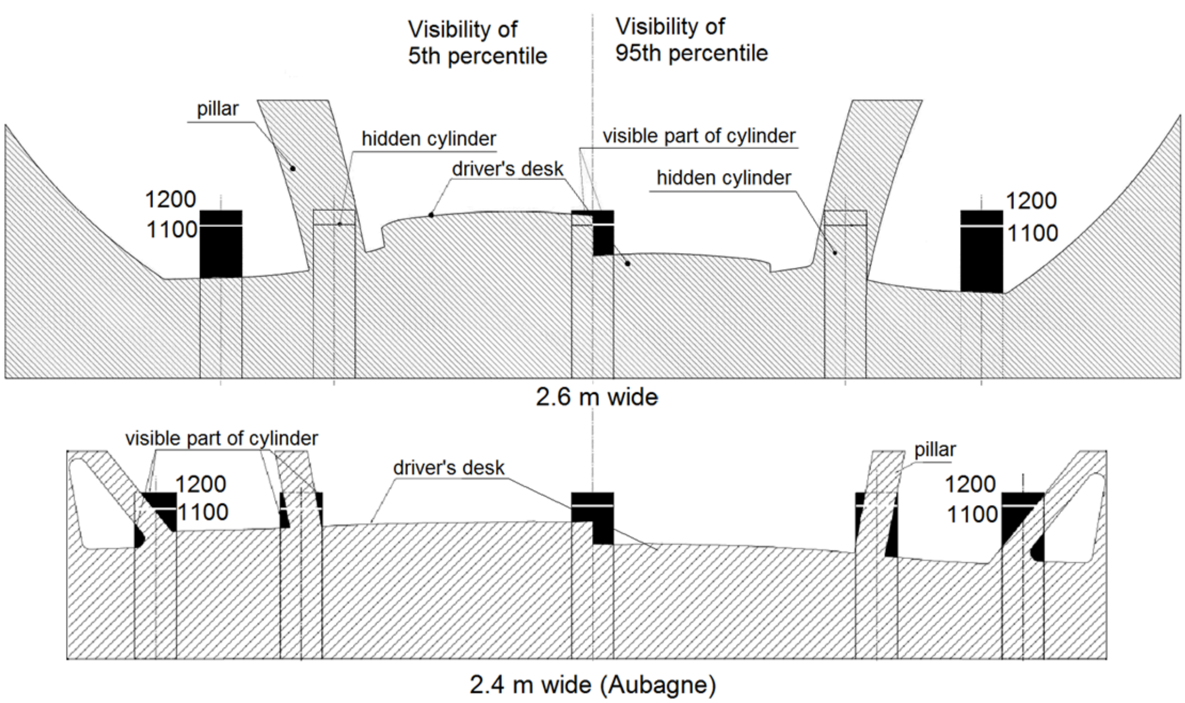

FIGURE 9 Visibility in old design of driving cab (*top*) and visibility in design meeting new requirements (*bottom*).

(a) (b)

FIGURE 10 (*a*) Old design and (*b*) new design (Aubagne).

CONCLUSIONS

The updated version of the guidebook should be easier to apply for manufacturers as well as for French public authorities in charge of transport policy. It was important to raise awareness among public authorities of the impact on safety of a design choice.

As of 2015, only one operating rolling stock fulfills the requirements of the guidebook, and five projects of rolling stock purchases consistent with the guidebook are in progress. The experience of this new generation of rolling stock will be looked at.

Moreover, the European standardization committee has launched work on adapting conventional railway standards to urban rail. In this context, a standard for the tram driver's cab will be created. The STRMTG will participate in the European standard working group to present the approach of the French working group. To that purpose, it is planned to have an official English version of the guidebook available on the STRMTG website at the beginning of 2016.

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State of the Art in Light Rail Alternative Power Supplies

John Swanson
John Smatlak
Interfleet Technology Inc.

Since the beginning of electrified rail transit in the 1880s, the conventional overhead contact system (OCS) has been the preferred power distribution method for light rail, streetcar, and tramway systems (referred to collectively in this paper as "light rail") throughout the world. Although a number of other approaches have been tried, all were ultimately found wanting. More recently, however, several modern versions of alternative power supply options have entered the marketplace—including onboard energy storage and ground level power supply—allowing operation of vehicles without an OCS ("off wire") over part or all of the alignment.

The application of alternative power supplies is a complex subject that is best approached from a systems viewpoint rather than just the vehicle or the electrification system. In the end, the goal is to provide reliable, continuous traction power to the rail vehicle, and this can be done in a number of ways. Followers of this subject will have seen many papers over the years that have identified, described, and evaluated many of these methods.

PURPOSE

The purpose of this paper is to examine progress during the last decade in the rapidly changing development of alternative power supply for light rail and to identify major technological advances and trends likely to affect the industry in the coming decade.

METHODS

The authors have conducted an ongoing literature survey and utilized personal experience, onsite visits, and collaborative information exchange with suppliers and users of the technology to develop this paper.

RESULTS

In 2005, no light rail systems in commercial service used onboard energy storage for off-wire operation, and only one system used ground level power supply (Bordeaux). It was expected that, by the end of 2015, eight cities would have ground level power supply systems in commercial service, and nine systems would be using onboard energy storage for off-wire operation (growing to 13 by the end of 2016). Several more systems of both types are also under construction. Development of battery, supercapacitor, flywheel, and hybrid onboard energy storage systems also continues as does onboard power generation using hydrogen fuel cells.

CONCLUSIONS

1. Alternative power supply methods for light rail are entering a new phase of development. Compared with 10 years ago, a significantly larger number of "early adopter" systems are either in commercial service or under construction. Although that number is still small compared with the more than 400 light rail systems worldwide, interest is strong, and the experience gained in operating these systems is expected to facilitate additional improvements and provide specific information on operating costs, including the life span of energy storage devices, and therefore, life-cycle costs. This will ideally provide decision makers with additional points to consider and some initial hard data that they currently cannot access.
2. Proprietary technology issues remain a major factor.
3. Application of the technology remains very project specific and may require vehicle performance trade-offs. Design requires careful analysis of alignment and duty cycle, including local climate factors. More sophisticated tools are needed to properly analyze the various system characteristics and consider a variety of scenarios to arrive at a reliable, cost-effective off-wire system design.
4. Onboard energy storage has multiple uses; it is also used for energy savings by increased recuperation of regenerative braking.

BACKGROUND

Since the beginning of electrified rail transit in the 1880s, the OCS has been the preferred power distribution method for light rail, streetcar, and tramway systems (referred to collectively in this paper as "light rail") throughout the world. Although a number of other approaches have been tried, all were ultimately found wanting.[1] More recently however, several modern versions of alternative power supply options have entered the marketplace, including onboard energy storage and ground level power supply, allowing operation of vehicles without an OCS (off wire) over part or all of the alignment.

The application of alternative power supplies is a complex subject that is best approached from a systems viewpoint rather than just the vehicle or the electrification system. In the end, the goal is to provide reliable, continuous traction power to the rail vehicle, and this can be done in a number of ways. Followers of this subject will have seen many papers over the years that have identified, described, and evaluated many of these methods.

For those who are new to the subject, there are three basic means as well as emerging hybridized combinations (indicative of how rapidly the technology is evolving):

- Ground-level power supply (GLPS): power continuously supplied to the vehicle at ground level through direct contact with a conductor or inductively;
- Onboard energy storage system (OESS): power stored on the vehicle, using flywheels, batteries, supercapacitors, or a combination thereof, recharged periodically through regenerative braking and contact with a power conductor; and
- Onboard power generation system (OPGS): power continuously generated on the vehicle, as required, through hydrogen fuel cells, microturbines, or diesel engines.

The advantages of these alternative power supply methods center around providing improved aesthetics and reducing conflicts with other users of the street space that include utilities, bridges, traffic signals and other overhead structures, as well as special events (such as parades), and so forth. In the case of the OESS, the related infrastructure is also simplified, in some cases reducing short term (capital) and long term (maintenance) infrastructure costs.

The disadvantages include increasing the complexity of the vehicle (OESS) or the wayside infrastructure (GLPS) that may lead to increased capital costs or vehicle life-cycle costs, or both. With the OESS, there are also weight, space, and performance trade-offs, as well as the unknown life expectancy of OESS elements.

CURRENT STATUS WORLDWIDE

In 2005, no light rail systems were in commercial service that used an OESS for off-wire operation, and only one system was using a GLPS (Bordeaux). After a relatively slow start, the following were expected to be in commercial service by the end of 2015:

- Eight systems using GLPS, with at least five more under construction (Table 1);
- Nine systems using an OESS for off-wire operation, with at least eight more under construction (Table 2); and
- Four systems using an OPGS (diesel hybrid light rail vehicles) for off-wire operation (Table 3).

Significantly, the lengths of the off-wire segments, whether powered by a GLPS or an OESS, have been slowly increasing, and in a few cases, the entire length of a line uses alternative power supply.

Meanwhile, the supporting development of battery, supercapacitor, flywheel, and diesel hybrid alternative power systems, as well as onboard power generation using hydrogen fuel cells, has continued on at least 27 prototype/development vehicles (Table 4), with more to come. A number of systems are using onboard energy storage primarily for energy saving purposes (Table 5), which as a side benefit, is also in many cases capable of moving a vehicle very short distances off wire (e.g., out of an intersection).

The following tables provide an overview of the current status (October 2015) of vehicle-borne alternative power supplies for light rail application.

In addition to numerous prototype vehicles used for evaluating onboard energy storage systems for energy savings (see Table 4), the light rail vehicles listed in Table 5 are known to have been fitted with such systems for commercial use. The list is not comprehensive, and further research will be required to compile a more complete list.

TABLE 1 Ground-Level Power Supply Systems (GLPS)

City	Operational	Length, Off Wire	Length, System	Supplier	Technology	Vehicles
Bordeaux, France	2003	13.6-km total segments	44 km, 90 stops, 3 lines	Alstom	APS	79 CITADIS vehicles
Angers, France	2011	1.5-km total segments	12 km, 25 stops	Alstom	APS	17 CITADIS vehicles
Reims, France	2011	2-km segment	12 km, 23 stops	Alstom	APS	18 CITADIS vehicles
Orleans, France	2012	2.1-km segment	12 km, 26 stops, Line B	Alstom	APS	21 CITADIS vehicles
Tours, France	2013	2-km segment	15 km, 29 stops	Alstom	APS	21 CITADIS vehicles
Dubai, Al Sufouh, UAE	2014	Completely catenary free	10.6 km, 11 stops	Alstom	APS II	11 CITADIS vehicles, 14 more in 2nd phase
Beijing, China	2015	4-km total segments	9.4 km Xijiao line	AnsaldoBreda/ CNR	Tramwave	31 SIRIO vehicles
Zhuhai, China	2015	Completely catenary free	8.7 km, 14 stops	AnsaldoBreda/ CNR	Tramwave	10 SIRIO vehicles
Cuenca, Ecuador	2016	1.2-km segment	10.5 km, 27 stops	Alstom	APS	14 CITADIS vehicles
Rio de Janeiro (Rio Porto Maravilha), Brazil	2016	Completely catenary free	28 km, 24 stops	Alstom	APS plus OESS (supercapacitors)	32 CITADIS vehicles
Lusail, Qatar	2018	22.7-km total segments	33.1 km, 37 stops, 4 lines	Alstom	APS	35 CITADIS vehicles
Sydney, Australia	2019	1.5 km	12 km CBD/ East Line, 13 stations	Alstom	APS	30 CITADIS vehicles
Florence (Firenza), Italy	201?	470 m	7.5 km, 18 stops, Line 2	AnsaldoBreda	Tramwave	SIRIO vehicles

Note: UAE = United Arab Emirates; CBD = central business district.

TABLE 2 Onboard Energy Storage Systems for Off-Wire Operation (OESS)

City	Operational	Length, Off Wire	Length, System	Supplier	Technology	Vehicles
Nice, France	2007	0.91-km total segments	8.7 km, 21 stops	Alstom	Battery, (Ni-MH) (SAFT)	20 CITADIS vehicles
Seville, Spain	2011	0.6-km line segment	2.2 km, 5 stops	CAF	ACR Evodrive supercapacitors	4 URBOS 3 vehicles
Shenyang, China	2013	Segments totaling 2.5 km	69.9 km, 65 stops, 4 lines	CNR Changchun	Voith supercapacitors	30 "dolphin" vehicles
Zaragoza, Spain	2013	2-km off-wire segment, charging at stops	12.8 km, 25 stops	CAF	ACR Freedrive battery/ supercapacitors	21 URBOS 3 vehicles
Guangzhou, China	2014	Completely catenary free, charging at stops	7.7 km, 10 stops, Haizu Circle Line	CSR ZELC	Siemens SITRAS ES supercapacitors (Maxwell)	7 vehicles
Nanjing, China	2014	90% catenary free, OCS only at stops and acceleration points	8 km, 13 stops, Hexi Line	CSR Puzhen	Bombardier Primove battery (Li-ion)	15 FLEXITY 2 vehicles
Kaohsiung, Taiwan	2015	Completely catenary free, charging at stops	8.2 km, 14 stops	CAF	ACR Evodrive supercapacitors	9 URBOS vehicles
Dallas, Texas	2015	Oak Cliff streetcar, 1.6 km	2.6 km, 4 stops	Brookville	ABB battery (Li-ion nickel manganese cobalt)	2 LIBERTY vehicles
Konya, Turkey	2015	1.8 km	21 km, 35 stops	Skoda	CATFREE battery (nano-lithium-titanium)	12 FORCITY CLASSIC 28T vehicles
Santos, Brazil	2106	0.4 km	11.4 km, 14 stops	Vossloh	ABB battery (Li-titanate)	22 TRAMLINK V4 vehicles
Seattle, Washington	2016	Seattle First Hill Streetcar, 4 km (downhill track)	4 km, 10 stops	Inekon	Battery (Li-ion)(SAFT)	6 TRIO 12 vehicles

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TABLE 2 (*continued*) Onboard Energy Storage Systems for Off-Wire Operation (OESS)

City	Operational	Length, Off Wire	Length, System	Supplier	Technology	Vehicles
Detroit, Michigan	2016	New M-1 streetcar line, (length tbd—60% of system proposed)	5.1 km, 20 stops	Brookville	ABB battery (Li-ion nickel manganese cobalt)	6 LIBERTY 12 vehicles
Doha Education City, Qatar	2016	Completely catenary free, charging at stops	11.5 km, 25 stops	Siemens	SITRAS HES battery (Ni-MH)/ supercapacitors	19 AVENIO vehicles
Granada, Spain	2017	4 segments totaling 4.95 km	15.9 km, 26 stops	CAF	ACR Freedrive battery/supercapacitors	13 URBOS 3 vehicles
Luxembourg	2020	3.6-km off-wire segment between Pont Rouge and Gare Centrale, charging at stops	16 km, 24 stops	CAF	ACR Freedrive battery/ supercapacitors	21 URBOS 3 vehicles
Nice	2018	Completely catenary free, charging at stops	11.3 km	Alstom	SRS with Ecopack (battery/ supercapacitors)	19 Citadis XO5 vehicles
Munich, Germany	201?	Planned English Garden extension, 1 km with 2 stops	8 km, 4 new stops	Stadler	Battery (Li-ion)	4 VARIOBAHN vehicles with batteries ordered (with 10 more prewired for future battery retrofit) All delivered, but only one vehicle currently fitted with batteries pending construction of new line.

NOTE: Li-ion = lithium ion; tbd = to be decided.

TABLE 3 Diesel Hybrid (Tram-Train) Vehicles for Off-Wire Operation (OPGS)

City	Operational	Length, Off Wire	Length, System	Supplier	Technology	Vehicles
Nordhausen, Germany	2004	8 km	9 km, 5 stops, Line 10	Siemens	Diesel hybrid	3 COMBINO DUO tram-train vehicles
Kassel, Germany	2006	28 km	30 km, 27 stops, Line RT4	Alstom	Diesel hybrid	10 REGIOCITADIS tram-train vehicles
Leon, Spain	2011	New FEVE tram train route Leon–Cistiernia	24 km	Vossloh	Diesel hybrid	4 TRAMLINK tram-train vehicles
Chemnitz, Germany	2014	Three new tram-train lines to Burgstädt, Mittweida, and Hainichen		Vossloh	Diesel hybrid	8 CITYLINK tram-train vehicles

TABLE 4 Development Prototypes

Installer	Operational	Location	Supplier	Technology	Vehicles
Alstom	1999	LaRochelle, France, Alstom test track	Alstom	Magnet Motor flywheel	CITADIS vehicle, STARS program. First use of charging at station stops
Alstom	2001	Karlsruhe, Germany, Line 1	Duewag	Turbomeca microturbine hybrid with CCM EMAFER flywheel energy storage	Ex-VBK GT8 vehicle, ULEV-TAP (Ultra Low Emission Vehicle–Transport using advanced propulsion) program.
Spie-Enertrans	2001	Marseille, France, Line 68	La Brugeoise	Innorail ground contact system	RTM PCC vehicle
Alstom	2002	LaRochelle, France, Alstom test track	Alstom	Innorail/APS ground contact system	CITADIS vehicle
Bombardier	2003–2007	Mannheim, Germany	Bombardier	MITRAC Energy Saver supercapacitors	DUWAG GTN6 vehicle
Siemens	2003–2005	Karlsruhe, Germany	Siemens	Diesel hybrid with 2 CCM flywheel energy storage units	AVANTO/S70 vehicle, ULEV-TAP 2 program.
Alstom	2006–2008	Rotterdam, Netherlands	Alstom	CCM flywheel	CITADIS vehicle, ULEV program
Kawasaki	2007–2008	Sapporo, Japan	Kawasaki	Gigacell battery (Ni-MH)	SWIMO-X demonstrator vehicle, RTRI sponsorship
Siemens	2007	Lisbon (Almada), Portugal	Siemens	SITRAS HES (energy saver) battery/supercap.	COMBINO PLUS vehicle
Tokyu Car	2007–2008	Sapporo, Japan	Tokyu Car	Battery (Li-ion)	HI-TRAM demonstrator vehicle, RTRI sponsorship
Alstom	2009–2010	Paris, France	Alstom	ECOPAK Supercapacitors	CITADIS vehicle, STEEM program
AnsaldoBreda	2010	Naples, Italy, 0.4-km test track and 0.6-km Poggioreale-Via Stadera line	AnsaldoBreda	Tramwave ground contact system (2nd generation STREAM)	SIRIO vehicle

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TABLE 4 (*continued*) Development Prototypes

Installer	Operational	Location	Supplier	Technology	Vehicles
Stadler	2011	Velten, Germany, test track	Stadler	Battery (Li-ion)	VARIOBAHN vehicle from MVG Munich order. One of four to be used on a future catenary free line through English Garden
Bombardier	2011–2012	Augsburg, Germany, 0.8-km Primove test track	Bombardier	Primove (inductive) current collector/battery	VARIOBAHN test vehicle
Fenit Rail	2011	Valencia, Spain	Fenit Rail	Fuel cell (hydrogen)/battery (Li-ion)/supercapacitors	Ex-SNCV FABIOLOS 3400 series vehicle, supported by local government funds.
KinkiSharyo	2011	Various U.S. cities	KinkiSharyo	Battery (Li-ion)	AMERITRAM demonstrator vehicle
AnsaldoBreda	2012	Florence (Firenza), Italy	AnsaldoBreda	Supercapacitors	SIRIO vehicle
AnsaldoBreda	2012	Bergamo, Italy	AnsaldoBreda	Supercapacitors	SIRIO vehicle
Hyundai Rotem/KRRI/ KAIST	2007–2014	Gyeonggi-do,Korea	Hyundai Rotem	Battery (Li-ion)/OLEV power transfer system	WTRAM prototype vehicle, Korea Railroad Research Institute. OLEV system, Korea Advanced Institute of Science & Technology
Vossloh	2013	Valencia, Spain	Vossloh	Battery (Li-ion)	TRAMLINK vehicle
Siemens	2014	San Diego, California	Siemens	Battery (Li-ion)	S70 vehicle, World record distance off wire (24.6 km)
CSR	2014	CSR China	CSR	Supercapacitors	4 module prototype vehicle
CAF	2015	Vitoria-Gasteiz, Spain	CAF	Battery (Li-ion)	URBOS 2 vehicle, OSIRIS project
Bom Sinal (Vossloh VLT licensee)	2015	Brazil	Bom Sinal	Battery	TRAMLINK VLT-based vehicle, CPDM-VE project

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TABLE 4 (*continued*) Development Prototypes

Installer	Operational	Location	Supplier	Technology	Vehicles
CSR Sifang (Skoda licensee)	2015	Quingdao, China	CSR Sifang Quingdao	BALLARD FC velocity fuel cell (hydrogen)	ASTRA 15T vehicle
Pesa	2015	Krakow, Poland	Pesa	Supercapacitors	SOLARIS TRAMINO vehicle
Toshiba	2015	Kagoshima, Japan	Alna Sharyo	Toshiba SCiB compact battery (Li-ion)	LITTLE DANCER Type A3 vehicle

NOTE: LRT = light rail transit.

TABLE 5 Onboard Energy Storage for Energy Savings

City	Year Operational	Area of Operation	Supplier	Technology	Vehicles
Portland, Oregon	2012	TriMet system	American Maglev	Supercapacitors (Maxwell)	27 SD660 vehicles retrofitted under TIGER III grant
Rhine-Neckar, Germany	2012	Mannheim to Heidelberg Line	Stadler	Bombardier MITRAC Energy Saver supercapacitors	30 VARIOBAHN vehicles
Rostock, Germany	2014		Vossloh	Vossloh Kiepe supercapacitors	13 TRAMLINK 6N2 vehicles
Seattle, Washington	2014	Sound Transit LINK LRT System	KinkiSharyo	Supercapacitors	3 existing 1500 VDC KinkiSharyo light rail vehicles retrofitted under TIGER grant
Cuiaba, Brazil	2015		CAF	ACR Evodrive supercapacitors	40 URBOS 3 vehicles
Wrockclaw, Poland	2015		Pesa	Supercapacitors	6 TWIST vehicles

NOTE: VDC = volts of direct current.

EVOLUTION

The last 5 years have seen increasing interest in unconventional means of propulsion throughout the transportation sector. For road transport vehicles, electric drives have become more and more commonplace. The battery, supercapacitor, flywheel, and fuel cell technology needed to power these electric drives has advanced considerably, with more efficient, smaller, lighter, and cost-effective designs becoming commercially available, along with increasing modularity, a trend that is expected to continue.

Although the automotive sector is clearly driving development of onboard power sources, it is interesting to note that of all the vehicles used to transport people today, the modern light rail vehicle has for some while been perhaps the best candidate for their use because light rail vehicles were already electrically propelled and have had the ability to regenerate braking energy as a standard feature. Market factors, such as low production quantities, cost, space requirements, weight, and complexity, as well as the inherent conservatism of the rail vehicle marketplace with its expectation that vehicles and their systems are typically expected to last 30 or more years, have initially slowed progress in this direction, but that is now changing.

The use of energy storage (both wayside and on board) to achieve energy savings continues to grow, particularly in Europe, where higher energy costs provide increased incentive. As a result, numerous projects have reported their analyses for calculating return on investment (e.g., calculating payback period). As a result of these studies, significant discussion on the subject of new versus retrofit of alternative power supplies has also emerged. Feedback from the car builders, combined with numerous studies, indicate that it is far more efficient to design in energy storage equipment from the beginning than to retrofit it. Fewer components and cleaner interfaces, less weight, and standardized elements, all combine to reduce cost and shorten the return on investment period.

The following sections review the most significant advances for the three primary types of alternative power supply technologies for light rail applications.

Ground-Level Power Supply

Background

The modern quest for wire-free zones for light rail systems began in 1999 when the ancient City of Bordeaux, France, wanted to build a new system that traversed an historically important area containing a 13th century cathedral and crossed an historic bridge over the Garonne without the use of overhead wires. It was not until 2003 that the first 3-km GLPS segments of the system opened, but today more than 31 km of GLPS are in commercial service worldwide, with more on the way.

This initial approach to providing off-wire capability concentrated on providing continuous ground level power to the vehicle, either through a switched direct contact system, such as APS or TramWave, or an inductive power transfer system such as Primove or OLEV Power Track. The continuous power supply approach is particularly advantageous in extreme climates that require heavy duty heating and air conditioning and for alignment sections with steep up-hill gradients that can quickly drain onboard energy storage systems. As seen in Table 1, the APS system is the most mature, having been through many teething problems to become very reliable and is now the market leader for ground level power supply. Other ground level systems are generally less well proven, but they are also now beginning to attract buyers. The suitability of GLPS in climates with heavy snowfall (and the attendant use of plows and road salt for snow removal) also remains an open question.

Issues

In all GLPS installations to date, a single supplier has provided both the vehicles and the power distribution infrastructure. Although this system-level approach is logical, the proprietary nature raises commercial issues that represent one of the biggest hurdles to the wider adoption of such systems. In the United States, sole source procurements of this nature are difficult to support under Federal Transit Administration procurement guidelines, and longer term, they lock an agency into a single technology and a single vehicle type from a single supplier, which carries some level of uncertainty about future support and further development. There are indications that some suppliers are willing to supply the GLPS system separate from the vehicle, but there have been no applications of this approach to date, and the power transfer system itself still remains a proprietary, sole source system.

The closely related issue of costs for a GLPS has also been a significant factor. The initial APS system installation was said to be eight times as expensive as the traditional OCS. Even though that price reflected significant engineering and development costs for the relatively short length of APS equipped track (3 km), no specific pricing data are available today, and so it seems clear that GLPS remains an expensive solution. In the opinion of the authors, it is perhaps possible that GLPS systems are best suited to supply as part of "turnkey" packages that offer the supplier the ability to provide vehicles and infrastructure as a package together with long-term maintenance. This approach could help optimize risk sharing and spread the costs over a wider scope of supply, thereby preserving necessary margins for the supplier while still offering the customer value for money.

Advances

The high costs of the complex underground infrastructure associated with GLPS has led suppliers to propose various noncontinuous solutions in the last few years. Although continuous GLPS systems already utilize an onboard battery for limited use in working around segment outages, adding a more robust onboard energy package provides two significant advantages: chiefly, the potential to simplify the infrastructure by limiting the use of the expensive GPLS components to locations at which it is (1) convenient for charging (e.g., at stops) or (2) needed for demanding power use (e.g., accelerating zone out of stops, hills, etc.),thus making the system more affordable. And, in the case of APS, this would also offer the potential to utilize regenerative energy from braking, which is not possible with the current generation of this technology. An example of this migration is found in the new tramway system currently under build in Rio de Janeiro, which will utilize supercapacitor-based energy storage on the vehicles in combination with Alstom APS ground level supply. An Alstom press release states that the system is completely catenary free, but the APS ground power supply will only be installed over 80% of the system.

Onboard Energy Storage System

Background

As the first GLPS system was going into service in 2003, efforts were also being made to provide vehicle power by use of an OESS that were based on battery, supercapacitor, and flywheel technology. Initial experiments focused on achieving energy savings through increased recuperation of regenerated braking energy, with off-wire operation a natural outgrowth. Nice, France, was the first city to introduce commercial off-wire operation using OESS, debuting in 2007 with two short segments.

Issues

From an operational perspective, the most significant trade-offs of the OESS approach to off-wire center around the fact that it is not a continuous form of power supply. The energy storage units need to be periodically recharged, and vehicle performance restrictions are typically implemented as part of optimizing the amount of energy storage to be carried on the vehicle. One example is “load shedding” which is relatively straightforward from a technical perspective, although its impact on operations is less clear. A good example would be reducing air conditioning in a scenario featuring a vehicle stuck in traffic, advantageous from an energy conservation point of view, but perhaps unacceptable from a customer service perspective in hot climates. In the end, careful design is required to find the optimal balance between energy storage capacity and the associated weight and space requirements. The additional equipment required to integrate the OESS also adds a further degree of technical complexity to the vehicle.

How charging is achieved also depends on the system design: if only short off-wire segments are to be traversed, then charging by the OCS is often a workable approach. However, if it is desired to have an extended off-wire section, or even a completely “catenary free” system, then it is necessary to recharge by other means, usually at station stops by either a conventional pantograph and an overhead conductor or by a ground level pickup or inductive charging system. This overhead “charging station” approach using modified pantographs has now been applied to new systems in Guangzhou and Nanjing in China; Kaohsiung, Taiwan; and Doha Education City, Qatar. This has the advantage of being very straightforward and nonproprietary. Reliability can be improved by incorporating an automatic location system to raise and lower the pantograph in the right places.

Another operational issue has to do with the inherent hazards associated with onboard energy storage. Maintenance practices will be affected by the presence on the vehicle of what, in many cases, is effectively a constantly charged power source. In addition, the prevailing use of the lithium ion type of batteries requires a significantly different level of care than battery technologies such as lead acid or NiCad commonly used on many types of rail vehicles.

From a cost perspective, the most significant trade-off inherent in the OESS approach is the initial impact on vehicle capital costs and the life-cycle cost of periodic replacement of the onboard energy storage units. Although detailed, unbiased cost information is generally not available (in common with other forms of alternative power supply), it is clear that the system operator will need to make significant allowances for ongoing renewals throughout the life of the vehicle, although as the technology improves, the time between upgrades may continue to increase, and the costs be reduced.

Advances

Advances in the area of OESS center around the continuing evolution of the energy storage units themselves. Of these, batteries (usually lithium ion) and supercapacitors (or a combination of the two) have enjoyed the greatest success so far, but continuing development of high tech flywheel technology (such as the GKN/Williams Hybrid Power MLC flywheel units) may well see its widespread use. An added advantage to all of these technologies is that they are supported by the world automotive market, where there is considerable research and development. Further, with careful design, it is also possible to utilize an OESS to achieve energy savings through improved capture of regenerative braking energy, which offers the potential for new systems to realize a reduction in the number of substations or for an existing system to add service or transition to a modern fleet with limited upgrading of the power network.

OESS systems with periodic charging are currently one of the most promising and widely available approaches available for those seeking an end to overhead wires. It will be interesting to see how the inherent trade-offs are dealt with once the new crop of systems becomes fully operational, particularly in cities with extreme climates in which power demand from vehicle heating, ventilating, and air conditioning systems is significant.

Onboard Power Generation System

Background and Issues

The OPGS approach to alternative power supply has been the slowest to develop with more modest commercial application than GLPS and the OESS. Advances have, however, been made in various approaches to fueled power generators on the vehicle. The trade-offs involve impacts on vehicle weight and configuration due to the related space impacts arising from both the power generator and the associated fuel storage and refueling facilities required.

In 2004, a small fleet of trams in Nordhausen, Germany, was locally fitted with a motor-generator package that was based on automotive diesel engines. Other European suppliers have followed a similar approach for light rail vehicles that needed to operate on both existing electrified lines within the city center and travel out to neighboring cities on existing regional rail lines without the expense of electrifying the entire line. Known in Europe as “tram-trains,” these vehicles are most commonly straight electric with dual voltage capabilities, but the diesel hybrid type has now also carved out a niche for itself, although it remains a limited market.

Advances

The most significant progress relating to onboard power generation involves the hydrogen fuel cell. It has been predicted that 2015 would be the year of the fuel cell, and that appears to be true. Toyota has announced that the first production series fuel cell cars will be built this year, and at least two fuel cell development light rail vehicles are under evaluation. Alstom has selected Hydrogenics to provide fuel cells for regional trains, while the CSR light rail vehicle and other rail vehicle demonstrators use Ballard, and no doubt, other light rail versions are under development. Costs are still high for the fuel cell units, and hydrogen supplies are not yet widely available, but this technology appears to be the wave of the future.

APPLICATION OF ALTERNATIVE POWER SUPPLIES

As noted earlier, the application of alternative power supplies to any light rail system requires a detailed system-specific approach and full consideration of all the variables involved so as to select the right technology and to optimize the size of the energy storage elements involved to provide the most cost-effective solution. This is far from being a simple task. At a minimum, the following variables will affect the analysis and design process for both GLPS and OESS systems:

Duty Cycle

- Operating headways (initial and future),
- Operating consists (single car, multiple cars)(initial and future),
- Distance between stops (off wire),
- Dwell times at stops (off wire),
- Dwell time at turnarounds (under OCS), and
- Operating time and distances under OCS.

Alignment

- Alignment curvature and gradients (off wire);
- Track arrangement (single track, double track, passing loop, crossing, junction, etc.) (off wire);
- Level of priority at traffic lights (none, predictive, priority);
- Number of road crossings between station stops (off wire);
- Degree of operation shared with road vehicles;
- Local speed limits;
- Availability of space for wayside substations, power feeders, and so on; and
- Future system expansions (including any off-wire sections).

Operating Environment

- Temperature-dependent vehicle loads (heating and air conditioning),
- Local climactic conditions (ice, snow, extreme heat),
- System regeneration limitations (line receptivity, regen initiation voltage, maximum regen voltage), and
- Energy costs and contractual arrangements (including peak demand charges, etc.).

Vehicle Systems

- Space available on board vehicles;
- Capacity, recharge time, size, weight, and cost of energy storage elements;
- Capacity, size, weight, efficiency, and cost of dc to dc inverter and ancillary equipment (power pickup elements, vehicle GPS/controls, etc.);

- Cooling, monitoring, charge–discharge control, maintenance approach for energy storage elements;
- Fire detection, prevention, and containment considerations for energy storage elements;
- Life expectancy of energy storage elements; and
- Replacement, disposal, or recycling of energy storage elements.

Similar operational, alignment and climactic requirements also apply to an OPGS as well as the following:

- Capacity, size, weight, and cost of onboard power generation elements;
- Capacity, size, weight, and cost of fuel storage elements;
- Cost and availability of selected fuel;
- Refueling periodicity/refill time;
- Wayside refueling equipment requirements;
- Cooling, exhaust, monitoring, control, maintenance approach;
- Fire detection, prevention, and containment considerations; and
- Noise and vibration mitigation.

Given all these variables, more advanced simulation tools are needed that will allow the designer to input and adjust the various parameters to obtain an optimal solution.

CONCLUSIONS

Alternative power supply methods for light rail are entering a new phase of development, offering system designers an important new tool in the toolbox. Compared with 10 years ago, a significantly larger number of early adopter systems are either in commercial service or under construction. Although that number is still small compared with the more than 400 light rail systems worldwide, interest is strong, and the experience gained in operating these systems is expected to facilitate further improvements and to start helping to answer important questions concerning life-cycle costs.

Issues affecting the application and development of alternative power supply to light rail include the following:

1. From a commercial perspective, proprietary technology issues remain a major point, particularly for ground power systems that involve significant equipment on the wayside. Ultimately, buyers want a mature (service proven) technology that conforms to agreed industry standards and allows designers to select from a range of competing suppliers. At this time, the relatively new field of alternative power supply is not in this position; it has limited standards and a series of competing, highly customized designs.

Decision makers have relatively little hard data on capital and life-cycle costs for GLPS and the OESS. Given the relative newness of the technology, the small quantities involved, and the competing proprietary designs, it may not be practical to expect that detailed, unbiased cost data will be available anytime soon. Instead, it may be necessary to consider technologies such as GLPS only within a project delivery framework that allows a single supplier to provide the vehicles, related infrastructure, and long-term maintenance as part of a turnkey package, thereby providing an opportunity to better allocate risks associated with capital and life-cycle costs.

There will, however, be an increasing number of projects in operation in the next decade, so it is possible that additional data can be obtained and analyzed. Together with standards for covering key related topics (e.g., safety measures for use of lithium ion batteries on light rail vehicles), both the suppliers and the buyers will be in a better position to continue developing alternative power supplies for light rail.

2. From a project-design perspective, application of alternative power supply technologies remains very project specific and may require vehicle performance trade-offs, particularly with the OESS. Its design is an iterative process that requires careful analysis of alignment and duty cycle, including local climate factors to balance the amount of energy storage capacity with the associated weight, space, and performance trade-offs. Given the significant impacts on multiple aspects of project design, balancing the need for an early commitment to off-wire operation (e.g., in the environmental phase) with traditional project design approaches may be challenging.

More sophisticated tools are needed to properly analyze the various system characteristics and to consider a variety of scenarios to arrive at a reliable, cost-effective off-wire system design.

3. Onboard energy storage has multiple uses; its application began with a desire for energy savings by increased recuperation of regenerative braking energy and has expanded into the ability to provide off-wire operation.

4. Although vehicles powered by hydrogen fuel cells hold great promise for the future, currently the most economical and straightforward approach to off-wire operation is onboard energy storage with periodic recharging. Recharging can be at station stops or combined with recharging under wired sections of the alignment. To operate such a system reliably, it seems likely that automating the recharging process, rather than relying on manual human actions, will be required.

5. From a project-planning perspective, the implications of including a commitment to off-wire operation in a project's environmental documentation, and then later altering the approach on the basis of further refinement of project costs and objectives, remains unclear.

SUGGESTIONS FOR ADDITIONAL RESEARCH

The following questions might be guides for future research:

- What industry R&D process changes could further speed up and improve development? What tools are needed to more efficiently analyze requirements?
- In considering new versus retrofit, what are the economics of buying a light rail vehicle as off wire capable, meaning that effective steps would be taken to facilitate the future addition of this capability? Besides reserving physical space, what other design elements need to be considered?
- Related to the above question, what new standards, or changes to existing standards, would be needed to facilitate application of these technologies and to ultimately lessen the impacts of proprietary technology?

- Various design issues are associated with frequent charging (e.g., at stops). These issues may include having to raise and lower the power transfer element; having the operator do this leaves a high likelihood of human error, while an automated system adds complexity and cost but increases system reliability. For systems with a mixture of conventional OCS and off-wire operation, are there conflicting requirements related to pantograph design? Other related design issues include power distribution for charging stations with a focus on the trade-offs between centralized substations feeding the charging points versus localized power conversion equipment at each point.

NOTE

1. Both onboard energy storage and ground level power supply (GLPS) were used for streetcar systems beginning in the 1890s. Most were quickly replaced with conventional overhead line, but some systems retained GLPS until abandoned (Washington, D.C., and Bordeaux, France, being two examples). Unlike modern GLPS, these early systems used separate positive and negative conductor rails that were not switched on or off as vehicles passed, which necessitated their placement in complex below-ground infrastructure.

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A Workable Solution to Conflicting Crashworthiness Requirements

GLENN GOUGH
Siemens Transportation

GEORGE C. HUD
Engineering Services

RICHARD CAREY
Metro Transit

Railway rolling stock, including light rail vehicles (LRVs) and streetcars, have traditionally been designed to protect passengers in a crash through the use of a very rigid structure to protect the occupied volume and an equally rigid anticlimbing device at the end of the car to prevent vehicles from telescoping into each other. Over the last decade, the emphasis has shifted to a design that relies on controlled deformation of the impact zone to dissipate crash energy, prevent telescoping, and reduce the effect of rapid deceleration on passengers, all while preserving the occupied volume. This crash energy management (CEM) design approach has been recently embraced in the North American LRV and streetcar community, but the original rigid body strength requirements have been retained in many vehicle specifications. This is often seen as a contradiction and perplexes designers. In a recent procurement, Minneapolis Metro Transit (METRO) and its consultant, LTK Engineering Services, worked closely with LRV manufacturer Siemens to interpret the requirements and implement a solution that met both the traditional static load requirements and the newer CEM requirements, proving that the two are not necessarily in conflict.

Siemens Model S70 LRVs were introduced to the Twin Cities in October 2014 after extensive testing. This was an order of 59 new LRVs: 47 LRVs to operate on the METRO Green Line and 12 LRVs for enhanced service on the METRO Blue (Hiawatha) Line. The new LRV delivery will ultimately provide both lines with enough LRVs to operate three-car trains during peak times and special events to meet growing ridership demands.

The technical specification for the Minneapolis Central Corridor LRV program provided the car builder two design options for the strength of the car body: the traditional 2 *g* static strength or an alternative energy-absorbing design. The European rail community spearheaded the crashworthiness-based design approach and developed a design and safety standard EN 15227 to codify the requirements. Siemens was selected by the Metropolitan Council as the car builder for this project, and it proposed a vehicle based on the alternative energy-absorbing design principles. This was the first LRV vehicle for any U.S. operating agency to be designed and built to the alternative crashworthiness requirements. The end underframe module was designed to these standards and successfully dynamically tested to validate the energy-absorbing capabilities, performance, and capacities.

Siemens tested a two-stage CEM solution. The intent was to consume the entire first stage but not trigger the underframe into collapse, which engages the second stage. The stages are not in the static strength load path (i.e., a 2 *g* end load), so they could be optimized to absorb energy without the requirement of being strong. This would present conflicting requirements. As a destructive test of a full LRV was deemed impractical, a full-scale test of the CEM system was performed with an impact test rig. The results correlated closely to the design calculations, proving compliance with the specification and clearing the way for production of the first vehicle of its kind in North America.

INTRODUCTION

In 2011, METRO awarded a contract to Siemens Transportation to provide LRVs for the new Green Line, which would connect Saint Paul and Minneapolis. Additional vehicles were also procured to support an increased ridership on the original Hiawatha Line (Blue Line). The Green Line (formerly known as Central Corridor) represented the largest transportation infrastructure project to date in the Twin Cities. In keeping with METRO's commitment to providing safe, reliable, and environmentally friendly public transportation, the LRV specification contained provisions for the latest technological advancements to protect passengers and train crew in a collision. Although vehicle-to-vehicle collision risk is quite low on such a system, the risk of collisions with automobiles and highway trucks is higher because of the amount of in-street running and the number of at-grade crossings. CEM designs provide a forward crumple zone that absorbs energy on impact, providing a predictable and controlled response to an impact. This, in turn, minimizes the secondary effect of the impact between passengers and the seats in front of them or other permanent fixtures.

Siemens took on the challenge of implementing the first full-scale CEM system on an American LRV. This paper describes the challenge Siemens faced, that of adding new energy-absorbing structures to a proven design that was based on the protection of the operator and passengers through the use of a rigid car body. The success of the project can be attributed to a cooperative effort between Siemens, METRO, and LTK Engineering Services to interpret the specification in a way that delivered the best outcome for all parties, and ultimately, the riders of the system.

METRO AND THE GREEN LINE PROJECT

METRO is responsible for nearly all bus and rail public transportation services in the seven-county Twin Cities metropolitan area, including construction and operation of METRO—the region's growing network of transitways offering frequent, all-day service between stations with enhanced amenities. As shown in Figure 1, the current METRO system consists of two light rail transit lines (Blue Line and Green Line) and one bus rapid transit line (Red Line). Planning is under way for extensions of all three existing lines plus the addition of two new bus rapid transit routes (Orange Line and Gold Line).

The existing METRO Blue Line LRT service opened in 2004, running between downtown Minneapolis, the Minneapolis-St. Paul Airport, and the Mall of America. There are 19 passenger stations and one operations and maintenance (O&M) facility along the existing 12.5-mi (20.1 km) Blue Line route, and the guideway operating characteristics vary considerably, including in-street running, semiexclusive track with at-grade crossings, and exclusive grade-separated tunnels and flyover structures, with posted operating speeds ranging from 10 mph (16 km/h) to 55 mph

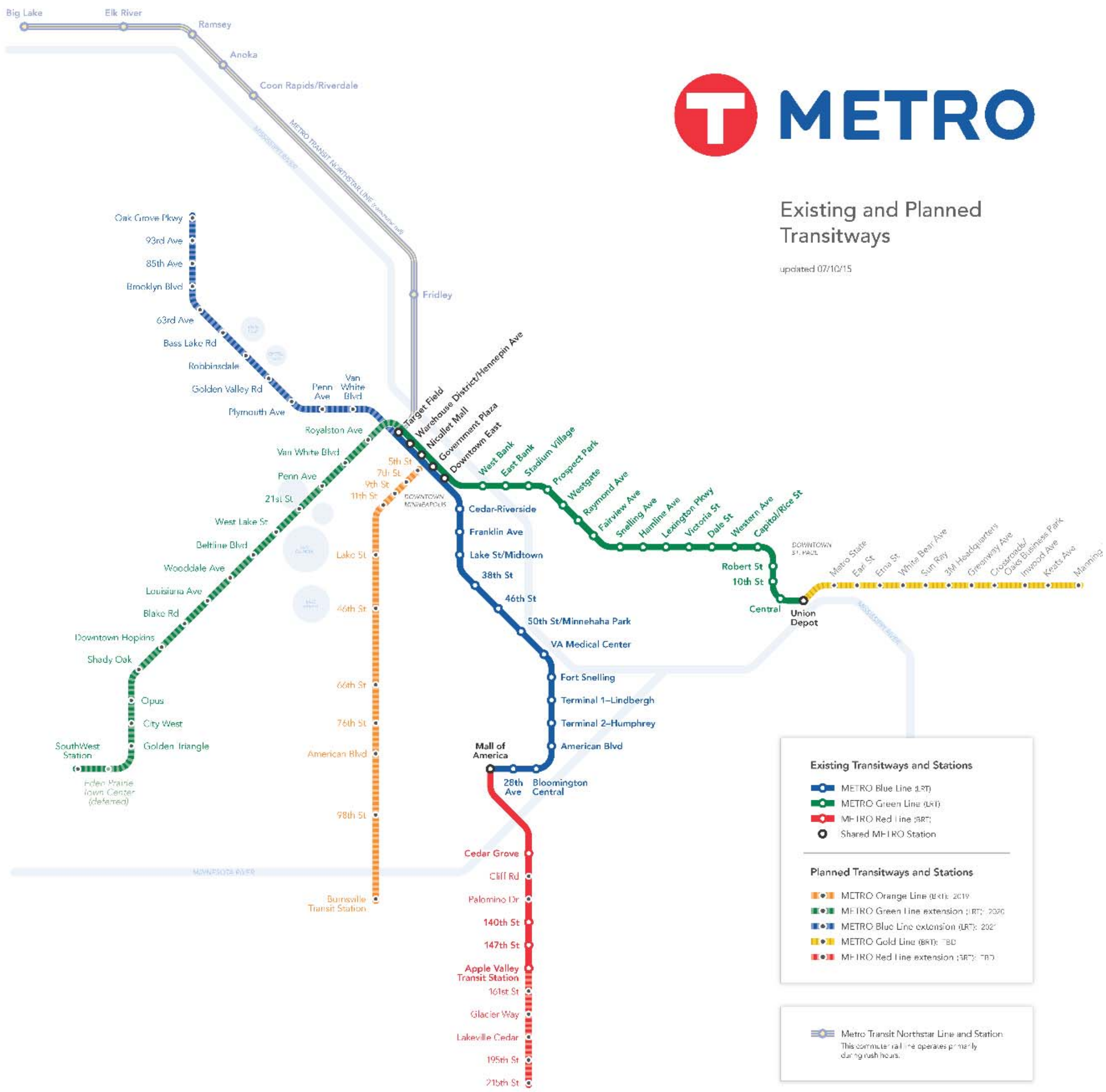

FIGURE 1 Minneapolis METRO light rail system map (*1*).

(88 km/h). Blue Line service had been provided with a fleet of 27 Bombardier LRVs but is now supplemented by 12 of the new Siemens vehicles to support three-car train operations. During 2014, the Blue Line served an average of 27,644 weekday passenger boardings.

The Green Line LRT service is the most recent addition to the Twin Cities' METRO system, opening in June 2014. The METRO Green Line provides a connection from downtown Minneapolis to the University of Minnesota, the Minnesota State Capitol, and downtown Saint Paul. As shown in Figure 2, the route is approximately 11 mi (17.7 km) long, with 18 new passenger stations and a light-duty O&M facility at the eastern terminus. The Green Line guideway is located almost entirely along the median of a four-lane urban arterial roadway, with in-street running in the downtown areas and a 0.5-mi (0.8 km) semiexclusive guideway segment on the east side of the University of Minnesota campus. The full route includes 68 at-grade

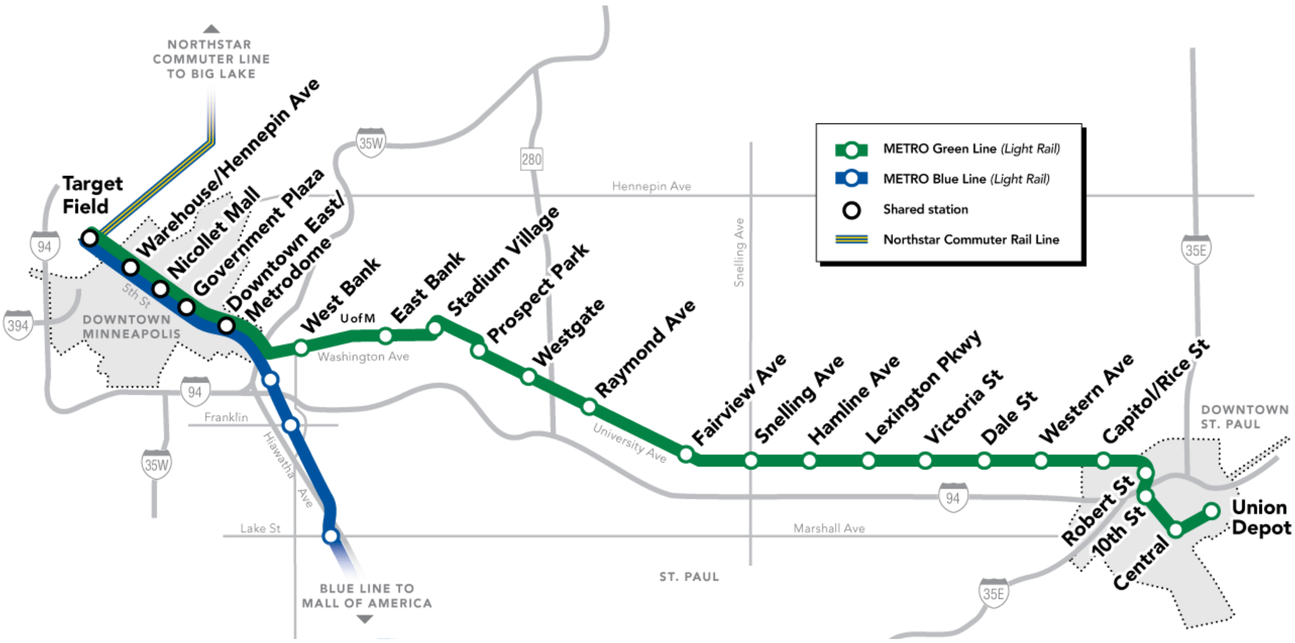

FIGURE 2 Minneapolis METRO Green Line (*1*).

public roadway crossings or intersections, most of which are controlled by traffic signal systems. METRO uses a fleet of 47 Siemens S70 LRVs to provide service along the Green Line, which is interlined with the Blue Line service through downtown Minneapolis. During its first 6 months of operation, the Green Line served an average of 34,500 weekday passenger boardings.

SPECIFIED STRUCTURAL PERFORMANCE REQUIREMENTS

To have confidence that the LRV being purchased would be able to satisfactorily and safely serve its intended purpose, METRO developed specific structural performance requirements for the vehicle. These requirements are listed in the technical specifications that were provided to interested prospective builders for their consideration and evaluation when developing their bid proposals for the METRO requested quotes. In the car body section of the technical specifications, METRO listed the structural performance requirements both for a strength-based 2 *g* design and the alternate energy-absorbing crashworthiness design. Table 1 summarizes the 2 *g* and the alternate energy-absorbing crashworthiness technical specifications requirements (*2*).

The technical specifications also contained structural test requirements to validate the analytical calculations. There are different prescribed test requirements depending on whether a 2 *g* design is pursued or a crashworthiness design is selected. For the 2 *g* design, the standard compendium of static tests is prescribed. However, for the alternative crashworthiness design, the specified tests are dynamic in nature. The dynamic tests are composed of two parts: an elemental test for the structural energy-absorbing elements and a car body crash test.

TABLE 1 Crashworthiness Specification Requirements Summary

Structural Design Load	Load Magnitude	Acceptance Criteria
2-*g* end sill compression	Two times the empty ready to run weight (2 *g*) applied longitudinally at the anticlimbers for both the empty ready to run weight AW0 and the crush load weight AW4.	No permanent deformation in any structural members. Margin of safety (MS) inboard of coupler anchor shall not be less than the lowest MS outboard of the coupler anchor. The lowest MS inboard of the coupler anchor shall not be in any part of the articulation or the yoke arms that attach the car body sections to the articulation.
Alternate energy-absorbing design	20-mph collision of two vehicles on level tangent track, vehicles at AW3 load, couplers and anticlimbers engaged in the crash. Impacting vehicle traveling at 20 mph (32 km/h) with brakes applied in emergency. Impacted vehicle stationary with brakes applied in full service.	Maximum acceleration of 10 g shall not be exceeded. Crush of carbody shall be limited to the zone outboard of the coupler anchor, or 5 ft (1.5 m). Progressive buckling and bending of the car body end structure.

The elemental energy tests are intended to demonstrate the energy-absorbing properties of the structural elements that are specifically designed for energy absorption, if any are used in the structure. These tests measure the force that is required to compress or crush a structural energy-absorber element in order to develop the force-displacement curves from which the absorbed energy can be calculated. The test specimens are manufactured in the same manner as the actual part to be used in the vehicle.

The car body energy test is intended to show that the car body meets the crashworthiness requirements of the technical specifications and to validate the analytical calculation models that were used in designing the crashworthiness features of the vehicle.

METRO Objective

In developing the technical specifications, METRO took into consideration the rapidly evolving shift in rail vehicle design philosophy, particularly in Europe, in that design for safety performance is just as important, if not more so, than design for strength. Considering that this change in design philosophy was still in a state of flux, and that there were many legacy 2 *g* designs still being offered by the car builders, METRO wrote the technical specifications in such a fashion that either design approach would be acceptable within specific prescribed acceptance criteria for each design approach.

Specifications: Traditional and Modern

With the advent of powerful computers and sophisticated structural analysis software, it finally became possible to perform computationally intensive crashworthiness calculations in a reasonable time frame. This development inspired car builders to utilize the new technology to design vehicles that demonstrated substantial safety improvements in collision scenarios. The automotive industry was at the forefront of this new technology and quickly adopted the design-for-safety paradigm over design for strength. Automobiles with enhanced crashworthiness features began to appear on the market in the 1990s. Today, virtually every automobile being sold has extensive crashworthiness features.

A similar safety-performance-over-strength analogy can be extended to the rail industry. Although railcar builders began exploring the incorporation of crashworthiness features substantially later than the automotive industry, they appear to be well on their way to a wholesale adoption of this technology. The European rail community spearheaded this effort, culminating in a 2005 release of a safety design standard, EN 15227, Railway Applications: Crashworthiness Requirements for Rail Vehicle Bodies, which covered various classes of rail vehicles. Several years later, the American Public Transportation Association (APTA) under the auspices of the American Society of Mechanical Engineers (ASME) issued a comparable safety standard, ASME RT-1-2009: Safety Standard for Structural Requirements for Light Rail Vehicles.

The EN 15227 and the ASME RT-1-2009 standards have many similarities but also numerous differences. The ASME RT-1-2009 standard can be viewed as a hybrid standard in that it retains many of the traditional static strength requirements but also introduces specific crashworthiness stipulations. Table 2 provides a comparison of the requirements in the METRO specifications, the ASME RT-1-2009 safety standard, and the EN 15227:2008 standard.

Advantage of Crash Energy Management

The primary advantage of a CEM design is that the behavior of the vehicles involved is more predictable, and the structure fails "gracefully" in a controlled manner. Although the energy imparted into the vehicle is merely a function of mass and speed, the CEM system slows down the actual crash event, reducing the peak acceleration that the vehicle, and its passengers, are exposed to. Reducing this acceleration peak, and creating a crumple zone that is more likely to stay engaged with the opposing vehicle, helps keep the vehicle upright, in-line, and even on the tracks. This reduces the probability of injury to crew and passengers as secondary impacts with seats, fixtures, and so forth, are minimized, as long as the passenger space is not compromised. Reduction in damage to the surrounding property and infrastructure is also minimized as the vehicles are less likely to leave the right-of-way.

THE SIEMENS SOLUTION

Problem

When the first S70 was delivered in 2002, safety-through-strength dominated structural requirements. Relatively recently, safety-through-managed-failure has become prevalent. In 2011, Siemens decided to update the S70 with dedicated CEM elements. This was influenced by two factors: (1) The METRO technical specification provided a requirement needing 600 kJ to be absorbed per vehicle, assuming equal damage; and (2) the ASME RT-1 LRV required 700 kJ to be absorbed. Previous S70s, following a strategy of progressive collapse, absorbed only 450 kJ.

TABLE 2 Requirements Comparison: METRO, ASME, and EN 15227

Specified Load	Acceptance Criteria
METRO Specification (*2*)	
20-mph (32 km/h) collision of two vehicles on level tangent track, at AW3 load, couplers and anticlimbers engaged. Impacting vehicle traveling at 20 mph (32 km/h) with brakes applied in emergency. Impacted vehicle stationary with brakes applied in full service.	Maximum acceleration of 10 *g* shall not be exceeded at any time after impact. Crush of car body shall be limited to the zone outboard of the coupler anchor, or 5 ft (1.5 m). Progressive buckling and bending of the car body end structure.
ASME-RT-1-2009 (*3*)	
Collision Zone 1—Low Severity Impact Scenario. Closing speed between two like LRVs of 5 mph (8 km/h). AW0 load condition, brakes at full service rate, coupler and/or front end covers configured in a typical service condition.	No structural damage to either LRV, with the possible exception of the element used to absorb the energy of the collision. This element can be either recoverable or replaceable. Progressive structural collapse beginning at the end of the vehicle. Highly localized plastic deformation of the occupied volume not affecting the ability of the structure to meet the requirements of this standard shall be allowed. The trucks of the vehicles shall remain on the track after the collision.
Collision Zone 2—Moderate Severity Impact Scenario. Closing speed between two like LRVs of 15 mph (24 km/h). AW0 load condition, brakes at full service rate, coupler, or front end covers, or both, configured in a typical service condition.	Maximum crush displacement measured from the anticlimber shall not exceed 300 mm (12 in.) in the direction of collapse. Maximum crush displacement of either colliding vehicle shall not differ more than 25% from the average maximum crush displacement of both vehicles. No loss of survivable volume in the passenger compartment (some local plastic deformation is allowed; however, deformation in the door-operating areas shall not infringe on the escape operation of the side door panels). Average vehicle acceleration of 5.0 g or less. Progressive structural collapse beginning at the end of the vehicle. Highly localized plastic deformation of the occupied volume not affecting the ability of the structure to meet the requirements of this standard shall be allowed. The trucks of the vehicles shall remain on the track after the collision.

(continued on next page)

TABLE 2 (*continued*) Requirements Comparison: METRO, ASME, and EN 15227

Specified Load	Acceptance Criteria
Collision Zone 3—Primary Passenger Volume. Closing speed between two like LRVs of 25 mph (40 km/h). AW0 load condition, brakes at full service rate, coupler, or front end covers, or both, configured in a typical service condition.	Crush damage shall be limited to the front cab sections of both colliding vehicles. Maximum crush displacement of either colliding vehicle shall not differ more than 25% from the average maximum crush displacement of both vehicles No loss of survival volume for passenger compartment (some local plastic deformation allowed; however, deformation in the door operating areas shall not infringe on the escape operation of the side door panels). Average vehicle acceleration of 7.5 g or less. Progressive structural collapse beginning at the end of the vehicle. Highly localized plastic deformation of the occupied volume not affecting the ability of the structure to meet the requirements of this standard shall be allowed. The trucks of the vehicles shall remain on the track after the collision.
Collision of LRVs leading end with street vehicle. Separately applied loads of 150 kN (33,700 lb) applied longitudinally at the centerline of the vehicle and a comer load of 100 kN (22,500 lb) applied in a direction normal to a surface point whose tangent is 45 degrees as measured relative to the longitudinal centerline of the vehicle. The loads shall be applied over any surface area on the leading end structure measuring no greater than 250 mm (10 in.) vertically x 500 mm (20 in.) horizontally. AW0 load condition, brakes at full service rate, coupler, or front end covers, or both, configured in a typical service condition.	No permanent deformation of LRV structural elements. Damage to decorative coverings or nonstructural elements is permissible. The trucks of the vehicles shall remain on the track after the collision.

(continued on next page)

TABLE 2 (*continued*) Requirements Comparison: METRO, ASME, and EN 15227

Specified Load	Acceptance Criteria
EN 15227:2008 *(4)*	
Design Collision Scenario 1. Collision obstacle: identical train unit at collision speed of 25 km/h (16 mph)	Reduce the risk of overriding: Up to 40 mm offset of colliding vehicles. At least one wheelset of bogie remains in contact with track. Wheel lift-off of up to 100 mm acceptable if ends "locked." Absorb collision energy in a controlled manner. Maintain survival space and structural integrity of the occupied areas: Reduction in length of passenger survival space not to exceed 50 mm in 5 m length, 100 mm at end of vehicle. Survival space for driver defined. Limit the deceleration: Mean longitudinal deceleration in survival spaces limited to 5 g for Scenarios 1 and 2 and 7.5 g for Scenario 3. Reduce the risk of derailment and limit the consequences of hitting a track obstruction: No significant permanent deformation of deflector and its fixations as defined by EN 12663. If obstacle deflector is overloaded, it shall not deform in such a way that it becomes detached.
Design Collision Scenario 2. Collision Obstacle 1: 80-ton wagon at collision speed of 25 km/h (16 mph) Collision Obstacle 2: 129-ton regional train at collision speed of 10 km/h (6 mph)	
Design Collision Scenario 3. Collision Obstacle: 15-ton deformable obstacle at collision speed of 25 km/h (16 mph)	
Design Collision Scenario 4. Collision obstacle: Small obstacle that can be displaced by the obstacle deflector on the car; deflector design force dependent on vehicle operational speed	

NOTE: All four collision scenarios assume unbraked vehicles and obstacles.

The progressive-collapse approach provides triggers or holes in the end frame to initiate a 2 *g* overload just behind the end sill. By adding dedicated crush elements, these higher energies could be better handled. Crush elements developed by the Siemens Vienna office were chosen, since their behavior was well understood.

The end structure of the vehicle needed to have three very distinct features that appeared to conflict:

1. Crash management,
2. A 2-*g* end frame, and
3. A structural snow plow.

A strategy of uncoupling these proved workable. Figure 3 shows the elements of the end frame with the integration of these features. The snow plow is included in the discussion, since it also appears to be an effective obstacle deflector that can be integrated into a CEM design. Also, simulations indicated that guidance of the first stage should be addressed.

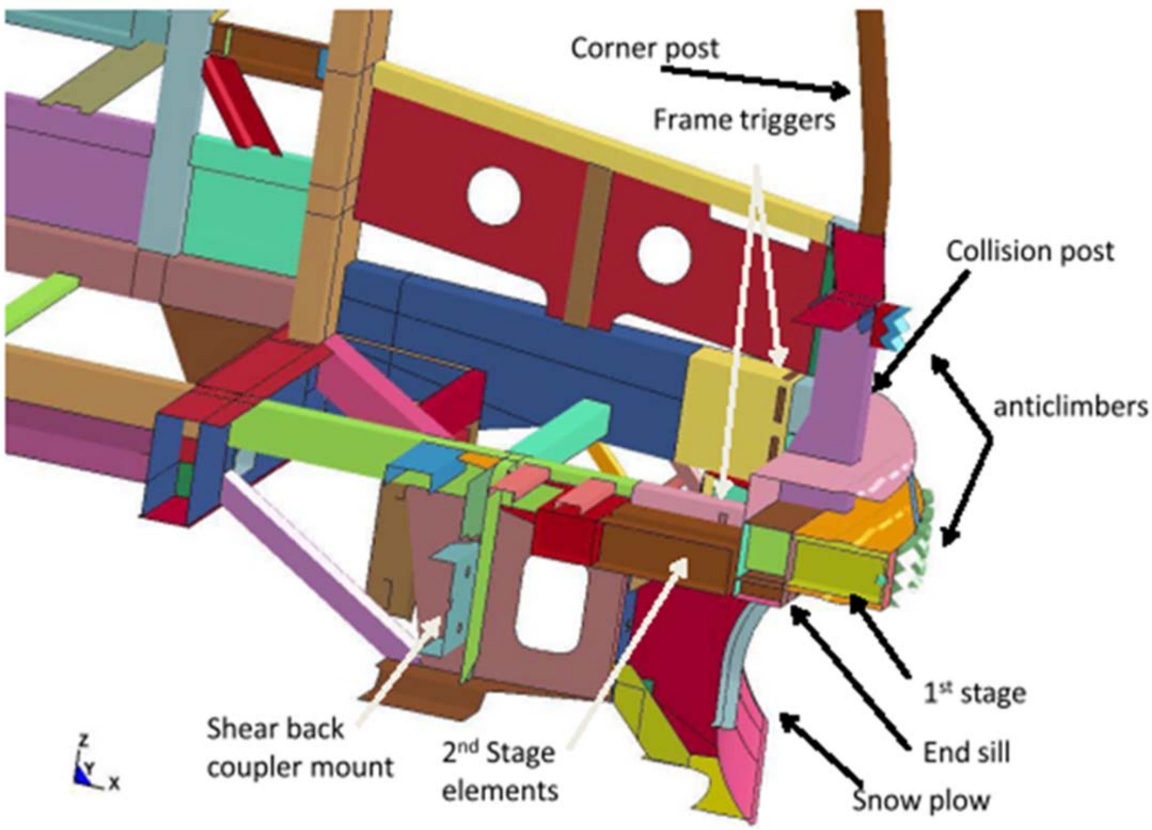

FIGURE 3 Design elements.

Solution

Crash management was uncoupled from the static strength requirement while not compromising safety. This required a review of the role of the anticlimber, end sill, and occupied space. Figure 4 shows the application of the static end load on the end sill, aft of the first stage crash elements and outboard of occupied volume. This approach is consistent with the Federal Railroad Administration's requirement for commuter and intercity vehicles. It is not necessary to preserve space that is not occupied.

The addition of crash elements forward of the 2 *g* end frame has been shown to reduce cab intrusion for a 25-mph (40 km/h) collision by 50%. It has reduced the cab intrusion to zero for the 15-mph (24 km/h) collision. For the 15-mph (24 km/h) collision, all structural repairs are expected to be performed external to the cab.

Traditionally, the anticlimber elements have been on the end sill. To minimize cab intrusion, crash elements have been added between the anticlimber elements and end sill. Because the crash elements do not support vertical shearing loads during early crushing, a guidance strategy was developed. The traditional anticlimber teeth appeared to create local rotations during initial contact. Therefore, triangle teeth that are asymmetric about the center line were used. They have a vertical gather range of ±25 mm. Also, a second set of teeth were added to the top of the collision posts. Once the first stage is exhausted, these engage to create a stable crush wall to control the crippling of the 2 *g* frame. Telescoping center sills are used to help stabilize the second stage. See Figure 5.

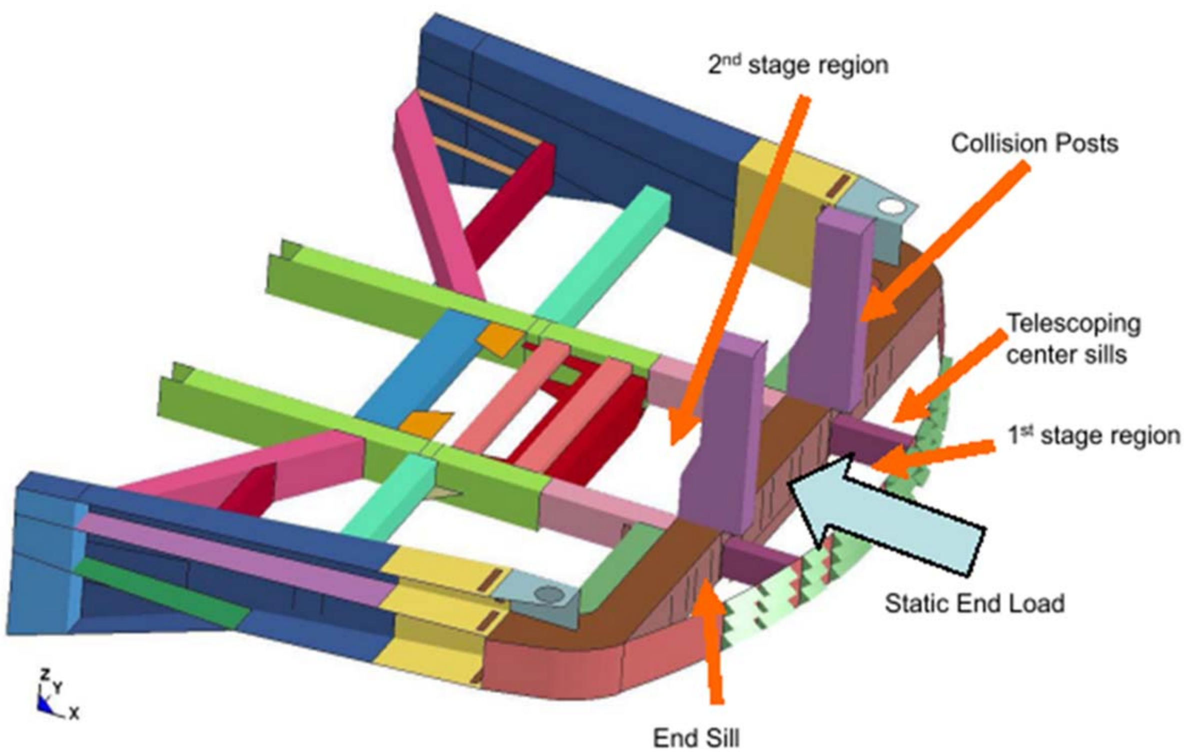

FIGURE 4 Application of the static end load.

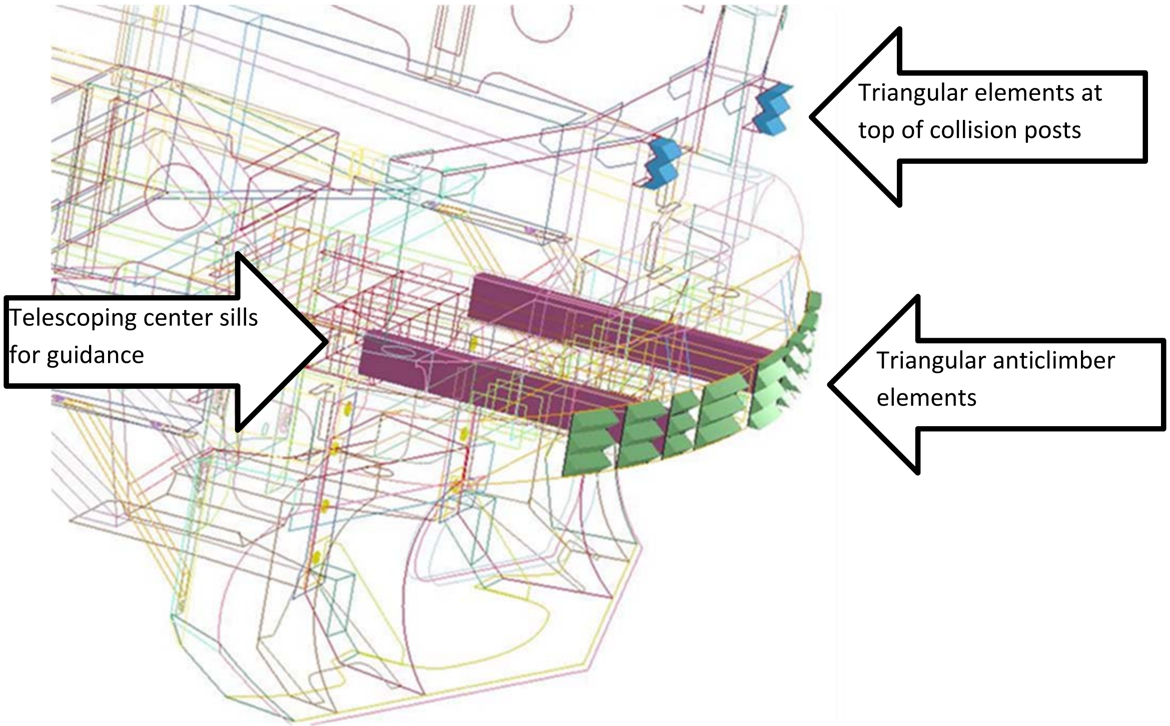

FIGURE 5 End frame showing guidance elements in anticlimber.

The snow plow structure was also uncoupled from the crash region (Figure 6). Crash elements are exhausted before the snow plow structure engages. This is important in a mixed environment with small road vehicles and pedestrians

Design Validation

Validation is critical for simulations. Unfortunately, testing is destructive. Full-scale testing is not viable for safety and economic reasons. However, testing at the component and subassembly level can be relatively inexpensive and very informative. Quasi-static crush tests on small components are low risk and can confirm material models and mode shapes. For small structures, the mode shape between an impulse and static load tend to be similar. For large structures, this is not the case. The crush tube in Figure 7 is made of ASTM A606 T4, a common carbon steel for car shells.

A significant subassembly was chosen for testing. The IMMI Center for Advanced Product Evaluation, in Indianapolis, Indiana, was chosen to perform the test. The assembly included the first stage and the side and center sills aft of the end sill containing the 2 *g* frame triggers. It was then mounted to a cart that was pulled into a rigid wall in the same fashion automobiles and trucks are tested.

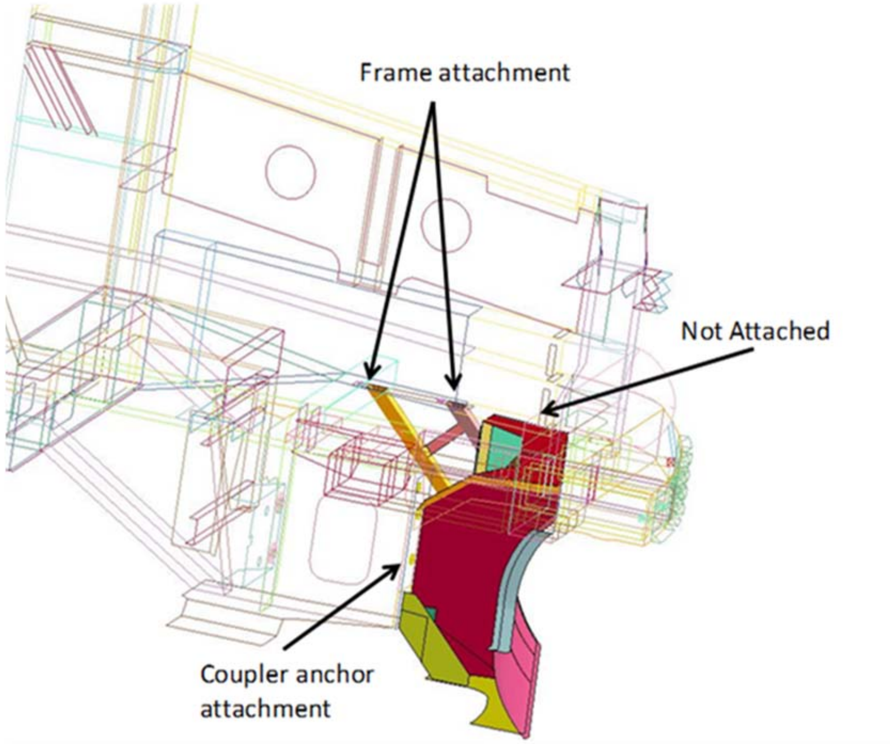

FIGURE 6 Snow plow configuration.

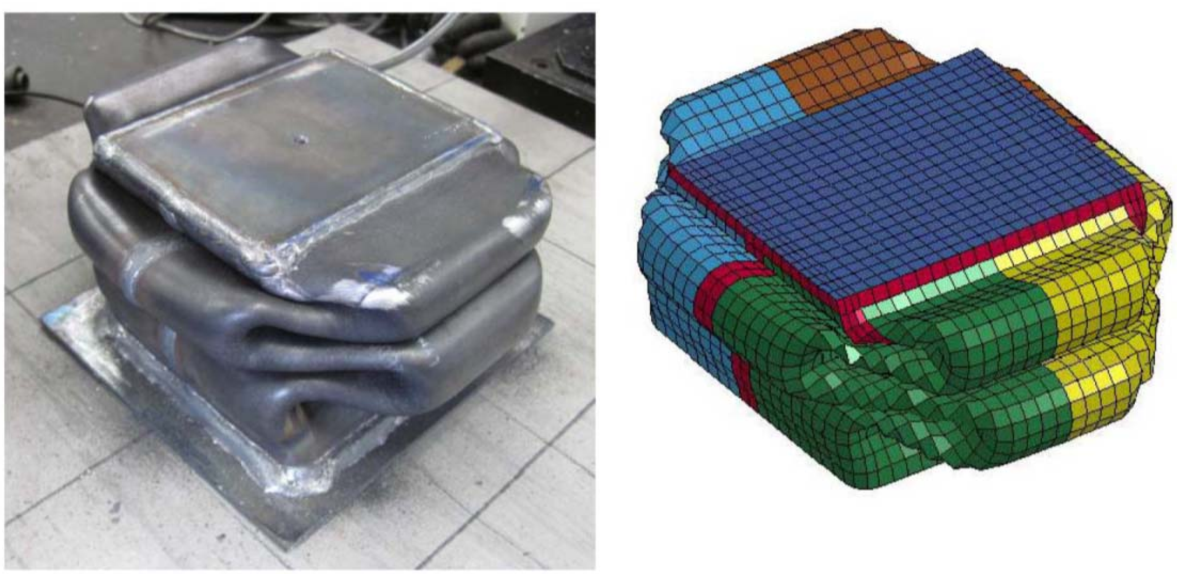

FIGURE 7 Component test and simulation comparison.

METRO raised a very important question: How is running a subassembly mounted to a 7.5 metric ton cart into a wall at 16.6 mph (27 km/h) anything like two AW3 vehicles running into each other at 20 mph (32 km/h)? Clearly, it is not similar, but a destructive test with finished vehicles is quite dangerous and economically prohibitive. However, the subassembly test can be simulated and compared with the physical test. This can provide confidence in the predictions for the full-scale vehicle by using the same software and model construction. Four criteria were established for the test shown in Figures 8 through 10:

- The first stage is consumed to a great extent.
- Second stage frame triggers should not activate.
- Energy consumption should be about 200 kJ.
- The force crush curve should increase as the crushing progresses.

Test results and simulation agreed well with respect to crush mode, crush depth, and energies. The simulation did overpredict initial triggering forces of the crush elements. This was attributed to the fact that the simulation model is ideal and free of weld distortion and other defects. Most important, both test and simulation showed that the first stage crash elements were almost entirely exhausted yet the second stage triggers remained intact. This indicated that force levels to activate crash elements and triggers were properly sized.

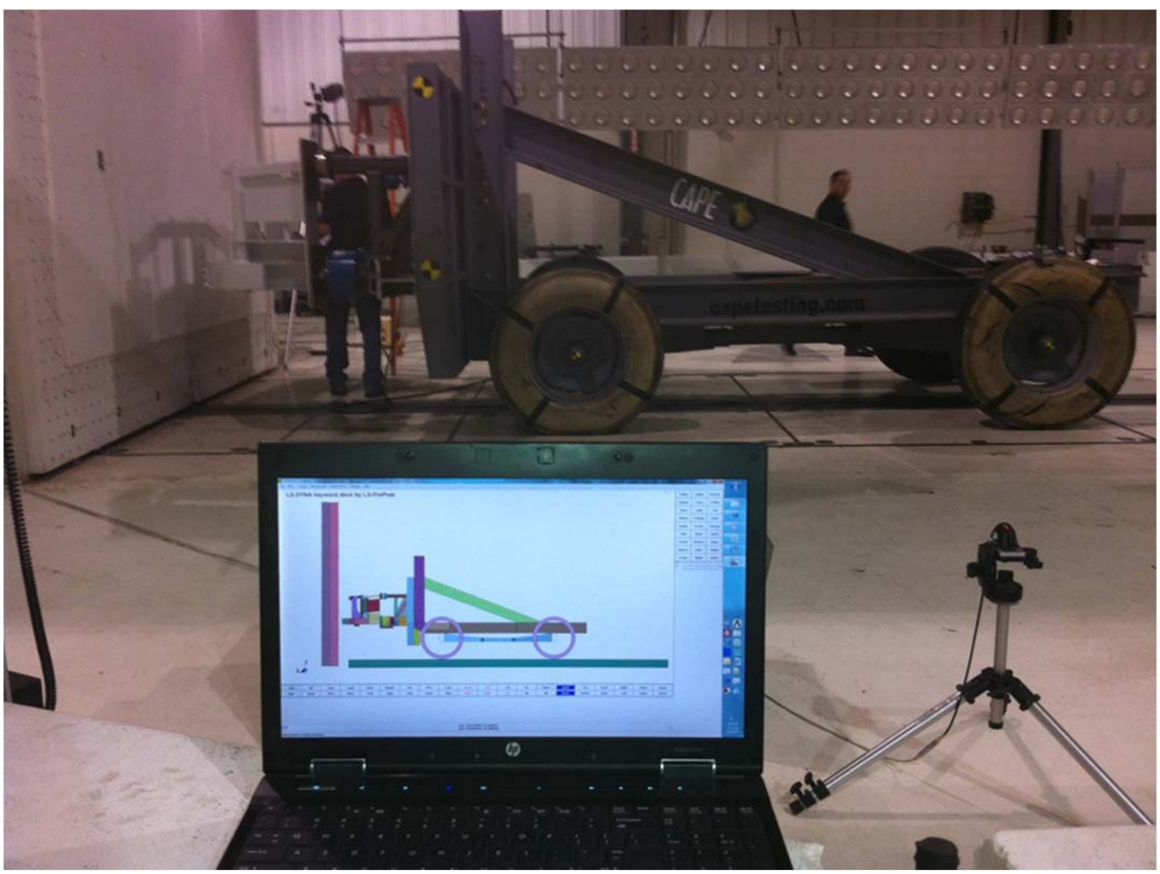

FIGURE 8 Physical test setup and image of the computer simulation.

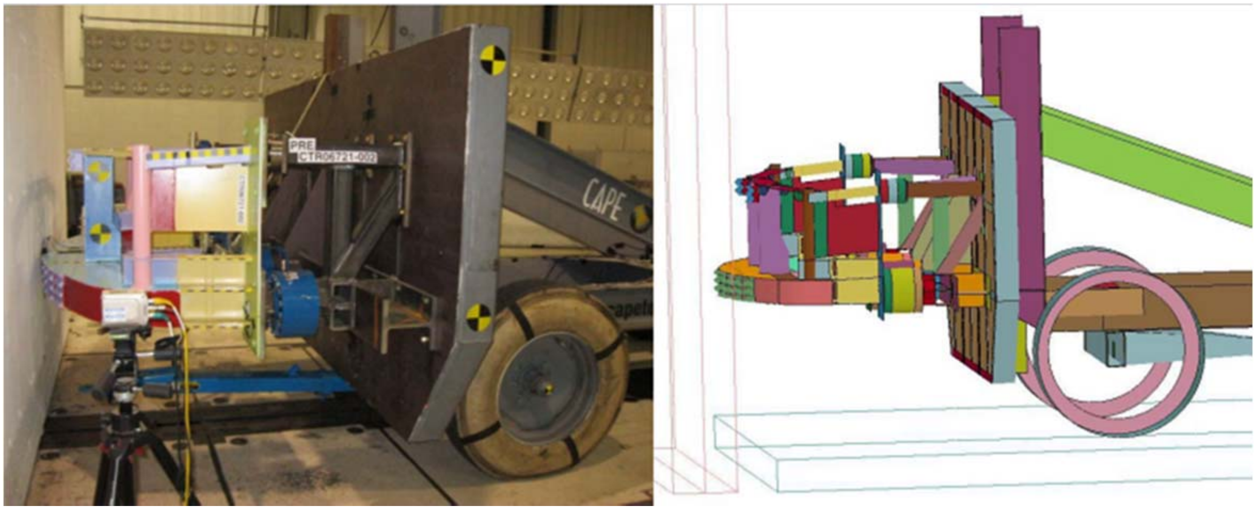

FIGURE 9 Test assembly mounted to test cart (*left*) and simulation (*right*).

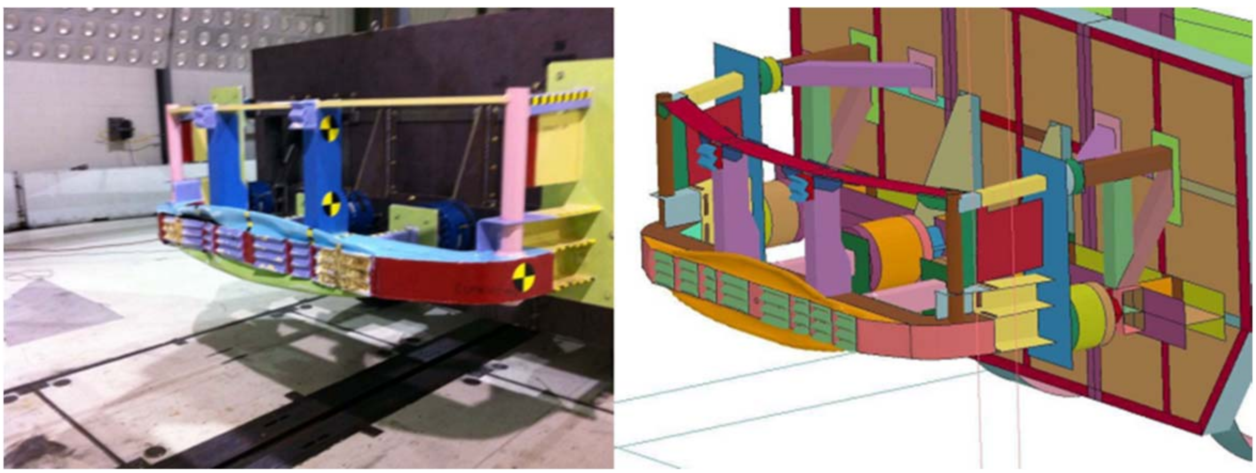

FIGURE 10 Postimpact: actual assembly (*left*) and simulation (*right*).

Discussion

Adding significant crush elements forward of occupied space has allowed a 50% reduction in cab intrusion for a 25-mph (40 km/h) collision between two 45 metric ton vehicles. It has reduced structural cab intrusion to zero for collisions up to 15 mph (24 km/h). To take advantage of this improved response, traditional requirements can be met if they are applied on occupied volumes and not the end of the vehicle as shown in Figures 3 through 10.

The snow plow was included because it provides structure to resist override and entrapment of objects of less size and mass. It has been shown that such an element can be integrated into a functional CEM design and provide obstacle deflection in the spirit of the EN 15227 standard. Interaction with small objects is anecdotally a significant source of damage and injury and implementing features to address small obstacles is recommended.

Discussions of adopting EN standards must address the requirements for structure above the underframe for asymmetric collisions. Currently, EN 15227 and EN 12663 can be met without corner or collision posts. This is expected to change in future revisions. Traditional end frame requirements, in considering ultimate failure and attachment strength, in North America have produced robust structures and are suggested for use.

For many years, there have been discussions about whether the static 2 *g* end load is excessive. The S70 was originally designed and sized to the 2 *g* end load. Although a simulation was performed during the original design, it was very basic and did not drive the design. As full CEM was implemented into the S70, it was found that a 2 *g* type structure is needed anyway to support loads developed during a crash. For the S70, 870 kN were applied to the end frame. In crash simulations, 2,000 kN are observed near the crash interface, while over 1,000 kN are seen at the articulations.

CONCLUSION

In a model team effort between operator (METRO), consultant (LTK), and car builder (Siemens), a proven traditional LRV designed for 2 *g* loading was successfully modified to provide CEM, providing the best of both worlds: safety through strength and safety through managed failure. This was made possible by both a cooperative approach to problem solving and by the design capability offered through modern simulation and testing techniques. The result is the modern, safe, and efficient Siemens S70 shown in METRO service in Figure 11.

FIGURE 11 Siemens LRV in service on Minneapolis METRO light rail system.

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Onboard Energy Storage System Applications on Streetcar Projects

JASON M. KRAUSE
MICHAEL TAGARAS
MARK COHEN
CHRISTOPHER R. WALKER
LTK Engineering Services

With the increasing number of projects for which off-wire capability has been developed and proven, predominantly in Europe, and with the continuous advancements in energy storage technology, interest is growing in using such applications on rail projects in North America. Indeed, several streetcar projects have implemented onboard energy storage solutions, and several more are in development.

The purpose of this paper is to describe the off-wire technical solutions that are being used in the first two North American projects—namely, the Dallas Streetcar project in Texas and the First Hill Streetcar project in Seattle, Washington. Service began in Dallas in April 2015, and the Seattle project was planned to be operational by late 2015. For each project, the paper addresses the operating environment, technology used, path that led to that solution, and lessons learned in achieving successful implementation. This paper also describes the next group of projects for which off-wire solutions are in various stages of implementation; these will provide technical information that will become available in the coming months. So far, these include the Wave Streetcar project in Fort Lauderdale, Florida; the M-1 RAIL streetcar project in Detroit, Michigan; the Oklahoma City Modern Streetcar project in Oklahoma; the expansion of the CityLYNX Gold Line streetcar in Charlotte, North Carolina; and DC Streetcar, a streetcar expansion effort using off-wire technology in Washington, D.C.

The authors have been directly involved in the implementation of most of the streetcar projects described above, including the review of candidate technologies, the development of technical specifications, procurement support, review of manufacturers' designs, and oversight of vehicle production and testing on behalf of the procuring entities. They draw from this experience to investigate similar information for other projects to develop this paper.

Two streetcar lines with onboard energy storage systems are planned to enter revenue service in 2015. Four more are in advanced stages of procurement, with potentially more to follow in short order. The requirements for each application are unique, such that the solutions will vary, if not in technology, in sizing of the equipment. These requirements are based on the unique duty cycle in each application.

Off-wire solutions using onboard energy storage technology have arrived in North America, initially for streetcar applications. With the projects in operation and nearing completion, and those emerging, there will be a useful body of knowledge to guide similar applications on future projects.

INTRODUCTION

Recent improvements in energy storage technologies, including supercapacitors and batteries, have paved the way for practical application to light rail and streetcar systems. What has now become quite commonplace in buses is being successfully introduced to several new streetcar systems in North America. Onboard energy storage allows these systems to operate in areas with sensitivity to traditional overhead contact systems. These sensitivities include the following:

- Historical preservation,
- Limited overhead clearance,
- Bridge reconstruction, and
- Stray current protection.

Two projects that are leading the way for onboard energy storage in North America are the Dallas Streetcar, already in operation, and the Seattle First Hill Streetcar, soon to be operating. This paper presents an overview of these two projects, along with a status update for five additional projects in varying stages of planning, design, and/or construction, with projects presented in the following order:

- Dallas Streetcar,
- Seattle First Hill Streetcar,
- Detroit M-1 RAIL streetcar,
- Oklahoma City Modern Streetcar,
- Charlotte CityLYNX Gold Line expansion,
- DC Streetcar, and
- Fort Lauderdale Wave Streetcar.

DALLAS STREETCAR

Project Description

Dallas Streetcar is a 1.6-mi (2.6 km) modern streetcar line in Dallas, Texas. Construction of the line began in May 2013, and it opened for revenue service on April 13, 2015. The line initiates at Union Station in downtown, traverses over the Houston Street Viaduct Bridge (off wire), and terminates near the Methodist Hospital in Oak Cliff (see Figure 1). The line includes four stations: Union Station, Greenbriar, Oakenwald, and Beckley. Revenue service is provided between 5 a.m. and 7:15 p.m., Monday through Friday, with no current weekend service. The cost to ride the streetcar is free. Dallas Streetcar is the first rail system in the United States to use wireless traction power, utilizing an onboard stored energy system as the streetcars cross the Houston Street Viaduct Bridge.

Implementation of the Dallas Streetcar project is a cooperative effort between the Dallas Area Rapid Transit (DART), the City of Dallas, and the North Central Texas Council of Governments (NCTCOG). The project received $23 million in initial funding through a federal TIGER grant awarded in December 2010. An additional $3 million in federal stimulus dollars were later granted, DART reallocated $22 million in local funds, and NCTCOG reallocated $31

FIGURE 1 Dallas Streetcar Houston Street Viaduct Bridge (looking north).

million in state funds to the project budget. The combined funding allows for construction of both the first phase (Figure 2) and next phases (Figure 3) of the streetcar project. The system is branded as the Dallas Streetcar and uses a unique logo, as shown in Figures 2 and 3 (*1*).

The area between Union Station and Greenbriar Station (including the Houston Street Viaduct Bridge) does not contain any traction power or overhead contact system (OCS) elements (although there is OCS within Union Station itself). To traverse the line (in both directions) in this region, the streetcar operates by off-wire technology. Traveling south, once the streetcar reaches the Greenbriar Station, the vehicle raises its pantograph and continues to Beckley Station under standard 600 volts of direct current (VDC) nominal electrified traction power. Traveling north, the streetcar continues to operate under OCS power from Beckley Station to Greenbriar Station, where the vehicle drops its pantograph, initiates the off-wire system, and continues over the Houston Street Viaduct Bridge to Union Station.

The Streetcar

A fleet of two modern streetcars are used to provide services during Phase I of the system. These vehicles were manufactured by Brookville Equipment Corporation (BEC) and are named Liberty Modern Streetcars (Figure 4). Two additional cars have been procured to supplement the fleet to support Phase II operations.

A Dallas Streetcar vehicle is a 70% low floor, dual truck, three car body section, dual articulated vehicle, manufactured from carbon steel, and using modern systems and features. In addition to the off-wire system [referred to as the Energy System Storage (ESS)] system, described below), amenities include closed-caption television, stainless steel seating, automatic announcements, and many others. Table 1 lists general specifications for a Dallas Streetcar vehicle.

FIGURE 2 Dallas Streetcar alignment: Phase I.

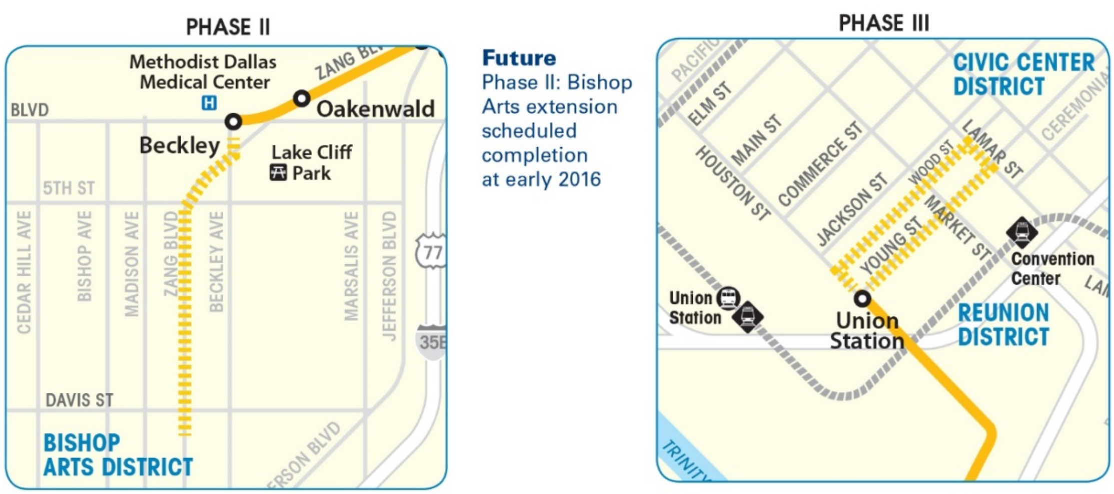

FIGURE 3 Dallas Streetcar alignment: Phase II and Phase III.

FIGURE 4 Dallas Streetcar.

TABLE 1 Dallas Streetcar General Specifications

Track gauge	Standard 4 ft, 8.5 in.
Boarding height	13.75 in. (350 mm)
Power supply	750 VDC (max. 925 VDC, min. 525 VDC)
Low-voltage power supply	24 VDC
Motors	4 x 65 kW or 4 x 99 kW
Maximum speed	44 mph (70 km/h)
Minimum turning radius	59 ft (18.0 m)
Vehicle length	66 ft, 5 in. (20.2 m)
Maximum height (without pantograph)	11 ft (3.35 m)
Wheelbase	39 ft (11.9)
Weight of car empty	83,200 lbs (33,739 kg)
Acceleration	3.0 mphps (1.34 m/s^2)
Brake deceleration (full service)	3.0 mphps (1.34 m/s^2)
Emergency brake deceleration	5.0 mphps 2.25 m/s^2)
Maximum grade	9%
Vehicle width	8 ft (2.46 m)
Percentage low floor	71%
Number of seats (AW0 or empty car)	34
Passenger capacity at AW3, or crush-loaded weight	137

NOTE: mphps = miles per hour per second.

Off-Wire Technology Solution

The off-wire system for a Dallas Streetcar vehicle consists of two large underfloor installed battery packs (referred to as ESS batteries); two roof-mounted liquid cooling systems, one for each battery pack (referred to as ESS Chillers); two microprocessor control/monitors; numerous interfaces with the streetcar vehicle control unit; and various diagnostic displays. Each ESS system provides power to one truck. Wireless operation is interlocked with the pantograph such that wireless operation can only be activated if the pantograph is down. Streetcar performance is the same off wire or under OCS.

The underfloor ESS battery pack uses lithium ion battery technology. The batteries are manufactured by Enerdel. Each ESS enclosure contains 15 battery subpacks, and every vehicle contains two of these enclosures (Figure 5).

The ESS system uses a battery management system integrated within the battery modules. This system monitors the condition of the batteries within the container, including temperature, voltage, state of charge, and overall health of the system; provides ground fault protection; and controls regulation of the charging and discharging of the batteries. The status of the batteries is made available through the controller area network bus.

Certain portions of the available status parameters of the ESS systems are available on the train operator display (TOD) within the cab. The battery management system transmits information over the controller area network bus to the vehicle control unit, which in turn, displays information on the TOD. Maintenance technicians, by the use of a password, can access detailed diagnostic information through the TOD.

The temperature of each ESS pack is maintained within a precise range to maximize performance. The roof-mounted cooling system (the chiller) is manufactured by Niagara Thermal Products and shown in Figure 6. BEC and Enerdel determined that the battery modules must remain at a temperature of 40°C or below to maximize performance. Each ESS enclosure uses two “cold plates” in conjunction with the roof-mounted chiller unit for climate control. The cooling circuit utilizes a mixture of 50/50 ethylene glycol, cooled by the chiller, to control temperature.

The ESS system was designed and sized to allow the streetcar to leave Union Station and traverse the Houston Street Viaduct Bridge to the Greenbriar Station without the need for any wayside traction power equipment. A detailed study was performed, using computer simulations, to determine the size and capacity of the ESS battery packs to ensure that the system capacity was sufficient, with a large margin of safety, to leave Union Station and travel to Greenbriar Station. The time spent “under wire” during the trip from Greenbriar Station to Beckley and back was modeled to simulate the charging time for the system. On the basis of the duty cycle of the Phase I system, including time off wire and time under wire, layover time, dwell time, and time to consider random stoppages, the size of the ESS system was finalized, along with its cooling needs to maximize performance.

The state of charge (SOC) for the ESS systems will be operated within the range of 60%–80%. From calculations performed by BEC and Enerdel, the ESS system will use approximately

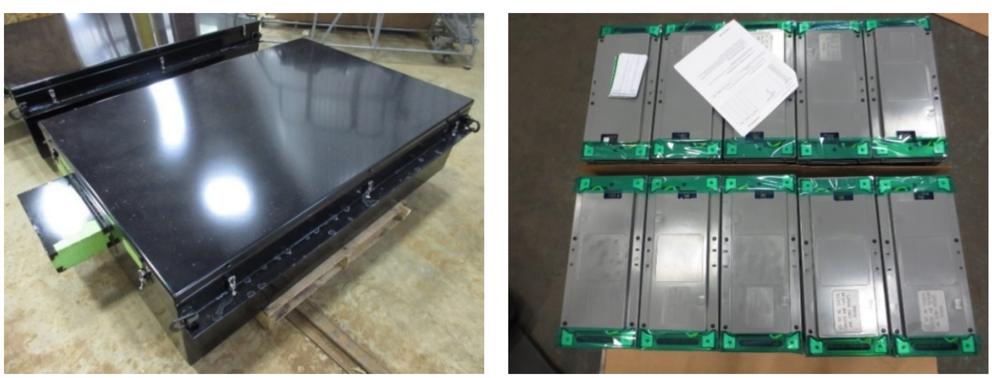

FIGURE 5 ESS underfloor battery container and batteries.

FIGURE 6 Chiller.

10% of its capacity during one complete trip. The ESS system was designed and sized such that the SOC will not decrease with time over the duty cycle of the system, specifically including the time under wire for charging.

The operator does not use a gauge or meter to determine if the ESS system is sufficiently charged to leave Union Station or Greenbriar Station and traverse the bridge. The TOD includes a go–no-go field in the upper right hand corner that is either green with the text "ESS Charge OK" or red with the text "ESS Charge Not OK." See Figure 7.

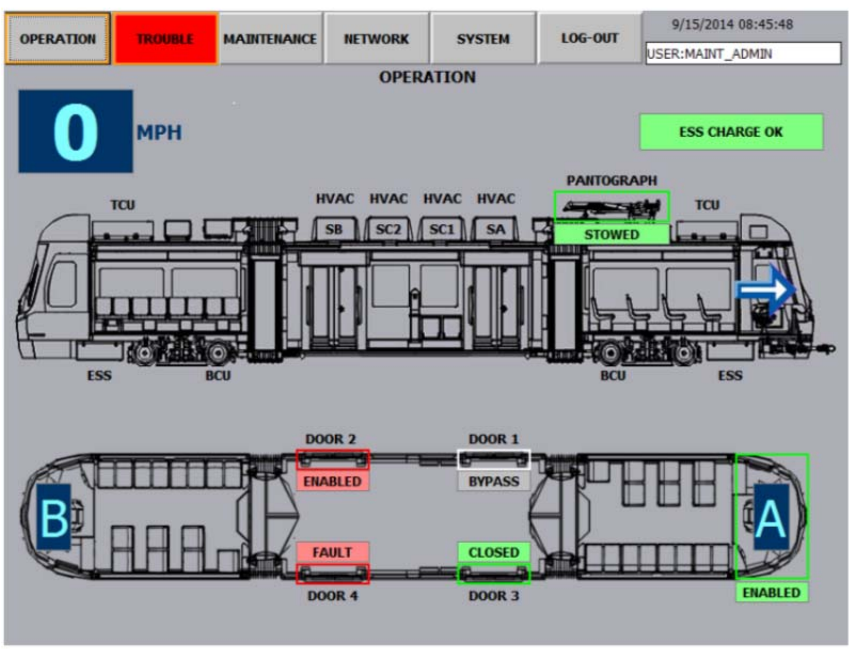

FIGURE 7 TOD screen showing go–no-go ESS state.

Maintaining Spare Equipment

Because of the complexity of the ESS battery containers with their multiple battery units and associated computer monitoring systems, two fully assembled spare ESS battery packs were procured (sufficient quantity for one car). These spare units are stored in specialized areas and are kept charged and ready for service by the use of a monitoring and charging unit (one unit for two spare ESS battery packs). Removal and replacement from the streetcar is by the use of a specialized jig and fork truck.

Lessons Learned

Determining the duty cycle of the system early in the project is paramount to finalizing the off-wire system size and capacity and thus minimizing project delays. The SOC range that the system will operate between should be determined early in the project because this operating range drives other technical elements. Working with operations personnel to determine how the off-wire system will be monitored by the vehicle operators allows minimal technical revisions to go–no-go gauges and layouts. Working with maintenance personnel to develop how the ESS battery packs will be removed and replaced, and how the spare units will be maintained, is critical to being ready for revenue service.

FIRST HILL STREETCAR: SEATTLE

Project Description

This section of the paper is an update to a paper presented at the Transportation Research Board in September 2012 (*2*). In 2007 the Seattle Department of Transportation (DOT) started revenue service on the South Lake Union (SLU) Streetcar, the first modern streetcar line in the Seattle area since streetcars were phased out in the1950s. Shortly thereafter, Sound Transit, the regional transit agency in the Seattle area, included approximately $133M for a second streetcar line to replace a planned light rail subway stop in a Sound Transit referendum for rail transit improvements. As part of its streetcar network planning process, the Seattle DOT worked with Sound Transit to define the line, and the two agencies eventually completed an interagency agreement to transfer funding and project development responsibilities to Seattle DOT. The First Hill Streetcar (FHSC) line was born. Conceptual engineering was started in 2009, followed by preliminary engineering in 2010 and final design in 2011. Construction started in mid-2012, with an opening currently planned for late 2015.

The FHSC line is approximately 3.8 km (2.4 mi) in length (see Figure 8) and will connect diverse and vibrant neighborhoods and mixed-use neighborhoods, as well as serve employment centers, medical centers, institutions of higher learning (Seattle University and Seattle Central Community College), and major sporting event locations (Century Link and Safeco Fields). It will provide connections to two Sound Transit light rail stations, AMTRAK, the Sounder regional rail system, and numerous bus and electric trolley bus (ETB) lines. The line is entirely in city streets and is characterized by long stretches of moderate grades and short

FIGURE 8 First Hill Streetcar alignment.

stretches of steep grades up to 9%. Overall the average grade is approximately 2.4%, with the first 2.1 km at an average of 3.4%.

Wireless Study

In early 2010, the Seattle DOT asked LTK Engineering Services, its FHSC systems consultant, to conduct a study of the feasibility of building a portion of the FHSC alignment without an overhead wire system, thus requiring the new streetcars to be able to operate without an overhead power source. Seattle has an extensive ETB network, and wireless capability was of particular interest in Seattle as a means to reduce or mitigate potential conflicts between existing ETB overhead wires and new streetcar routes with traditional overhead wire systems. The purpose of the study was to answer questions relating to streetcar–trolley bus integration, state of the art in wireless technology, appropriate onboard hardware, and candidate sections of track for wireless operation.

In April 2010, a report was produced that responded positively to these questions, and Seattle DOT chose to proceed with a procurement of streetcars with wireless capability. At that time, wireless operation was an emerging technology in the rail transit field, with approximately 5 years of development, although some bus applications had a somewhat longer history. Wireless operation is attractive in many locales for emergency recovery or aesthetic reasons, or both, in particularly sensitive or historic settings. Also, with today's interest in energy conservation, these systems are being developed to supplement, and not just intermittently replace, the normal traction power source by their ability to store regenerated energy.

Voltage Considerations

The existing Seattle SLU Streetcar fleet has a battery drive system for short emergency movements that operates at the normal battery level voltage of 24 VDC. However, this is not a practical operating voltage for repeated and extended off-wire operation because of associated high currents and operating temperatures. Vehicles in service and under development by major car builders have all used an enhanced battery or capacitor system, or both, at 400 VDC or higher, thereby permitting more reasonable levels of wireless operation. Some have achieved an off-wire capability of several kilometers. The study recommended that a battery drive system operate at a voltage approaching that of the overhead contact wire—for example, 600 VDC—for realistic applications involving a few thousand feet of wireless operation, particularly when substantial grades or curves are involved. In responding to these conclusions, the Seattle DOT decided in mid-2010 to proceed with its vehicle procurement based on a vehicle with an onboard energy storage system (OESS) operating near overhead voltage levels.

Vehicle Procurement Process

In mid-2010, Seattle DOT started its procurement of streetcars with OESS capability, and the chronology of the procurement is as follows:

- Industry review, late 2010;
- Request for proposals issued, March 2011;
- Proposals received, May 2011;
- Meetings with proposers, May 2011;
- Request for best and final offers (BAFOs) issued, August 2011;
- BAFOs received, September 2011;
- Selection of best value proposer, October 2011; and
- Notice to proceed, March 2012.

A contract was awarded to the Inekon Group (IG) for $26.7 million in March 2012 to provide six streetcars plus systems support, spares, and so on. A seventh vehicle was added to the contract in late 2012. See Figure 9.

Vehicle Technical Requirements

From the beginning of the process, the Seattle DOT intended to procure streetcars similar in size and type to its existing SLU cars: double sided, double ended, partial (or 100%) low floor streetcars approximately 20 to 22 m in length and 2.46 m in width so as to offer basic compatibility between the SLU and FHSC lines. As with the SLU line, the FHSC streetcars will operate singly as one-car trains.

FIGURE 9 Inekon streetcars.

A summary of the OESS requirements from the technical specifications and Inekon proposal is as follows:

- The vehicle is equipped with two onboard energy storage systems, one per truck, with the combined capability of operating the vehicle over the required profiles.
- The energy storage device is composed of lithium ion battery cells arranged to produce a high voltage storage device.
- A control unit is provided to interface with the propulsion, auxiliary power system, and heating, ventilating, and air conditioning (HVAC) system for the purpose of controlling energy storage device connections to those systems and monitoring the state of the energy storage device.
- The system interfaces with other train and wayside systems, at specific locations along the right-of-way that define the wireless segment, such that operation through the wireless segment can be accomplished without operator intervention. The system includes automatic controls to drop and isolate the pantograph circuit from the car high voltage bus before entering the area in which wireless operation is required and to automatically raise the pantograph and reconnect it to the car high voltage bus when on-wire operation is to be restored.
- A wireless operation switch on the operator console permits manual control of wireless operation by the train operator in the event that automatic operation malfunctions or wireless operation is required at other locations. Wireless operation is interlocked with the pantograph such that wireless operation can only be activated or deactivated if the pantograph is down.
- Wireless operation mode is annunciated on the driver's console.

- A bidirectional converter (chopper) is provided to both charge the energy storage device and control energy storage power flow to the auxiliary power system and propulsion system.
- Components are provided to monitor and balance storage device cell voltages to prevent damage to cells caused by too high or too low charge in specific cells.
- Temperature controls and forced ventilation equipment are provided to control the energy storage device cell temperature to keep the energy storage device cells at the optimum temperature for capacity and long life.
- Batteries are constructed using low maintenance lithium ion type.
- The energy storage device is installed in a temperature-controlled ventilated enclosure on the roof of the vehicle.
- The OESS is capable of providing an acceleration rate of 1.34 m/sec^2 and a top speed of 32 km/h with a fully loaded car.
- The vehicle is capable of providing normal service braking and emergency braking, spin/slide, mode change times, and so forth in OESS operation.

Key considerations for the wireless concept were the time or rate at which the vehicle would be discharging when operating wireless and the time or rate to recharge the OESS system. Lengthy charging times at the ends of the line could adversely affect operations and even require additional vehicles. Thus, a requirement was imposed that the OESS be charging whenever the pantograph was connected to the energized overhead wire or when the vehicle was in regenerative braking.

Wireless Segment

Initial investigations during the wireless study discussed above recommended three wireless segments, for a total of about 1.5 km or 20% of the length of a round trip alignment. After review of initial proposals, it was decided that a longer wireless capability was practical, and the request for BAFOs included as a desired option a wireless segment running the entire length of the inbound line, approximately 3.8 km. The inbound direction is predominately downhill, thus reducing the energy demand on the OESS. Vehicle charging occurs at the outbound terminus, at the inbound terminus after the OESS run, and during all pantograph operation on the outbound run.

Inekon Onboard Energy Storage System Car

The IG OESS car is based upon Inekon's successful conventional streetcar in service in Portland, Oregon, Seattle, and Washington, D.C. General arrangement, major dimensions, and several suppliers are the same. Figure 10 provides a general roof arrangement of the OESS car. Suppliers of major systems are as follows:

- Propulsion: ABB;
- Network: ABB/Selectron;
- Friction brakes: Knorr;
- Doors: Bode;
- HVAC: Moran;

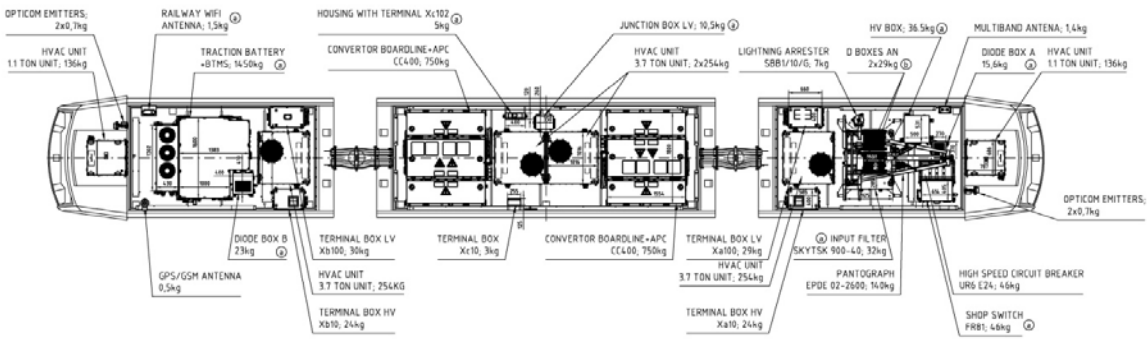

FIGURE 10 General roof arrangement.

- OESS battery: SAFT;
- Car shell; IG;
- Truck assembly: Penn Machine; and
- Final assembly (three cars): Pacifica (Seattle).

In 2013, the Seattle DOT executed a change order to add one optional car, bringing the total fleet size to seven, to add extra service to the existing SLU line.

The basic manufacturing plan included fabrication of all seven car shells and assembly of four cars by IG at the DPO facility in Ostrava, Czech Republic, where the original SLU cars were built. The remaining three cars underwent final assembly in the Seattle area at the new FHSC Operations Facility by Pacifica, a local company, under the auspices of IG.

The propulsion system (less traction motors) is supplied by ABB (Switzerland) and is based on their well-proven ABB BORDLINE CC400 ABB series. There are two propulsion packages, one for each truck, and each package is an integrated unit containing the following:

- Two propulsion inverters to allow single-axle control;
- One auxiliary converter;
- One onboard battery charger;
- One control unit;
- Line contactors, fuses, input filters, and braking choppers;
- Two choppers with LC-filter for energy storage system;
- Braking resistors; and
- Liquid cooled heat exchanger.

Figure 11 provides a view of the integrated CC400 unit chosen for this application. Space on the roof for a relatively small car such as this is at a premium and is further stressed by the need to accommodate the OESS batteries. The integration of the propulsion hardware into a single compact unit is aided by the introduction of liquid cooling, thus permitting necessary roof space for the OESS batteries and related equipment. A summary of the major characteristics of the vehicle is provided in Table 2.

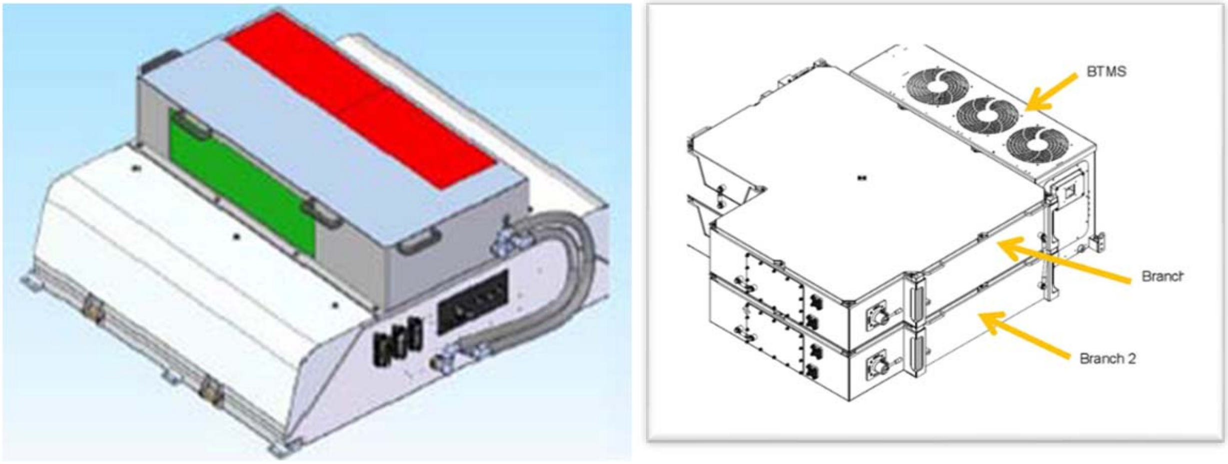

FIGURE 11 ABB integrated propulsion package (*left*) and Saft battery package (*right*).

TABLE 2 First Hill Streetcar General Specifications

OESS power supply	514 VDC
Low-voltage power supply	24 VDC
Motors	4 x 65W
Maximum speed	44 mph (70 km/h)
Minimum turning radius	60 ft (18.3 m)
Vehicle length	66 ft, 5 in. (20.2 m)
Maximum height (without pantograph)	11 ft (3.4 m)
Wheelbase	39 ft (11.9 m)
Weight of car empty	70,500 lbs (31,978 kg)
Acceleration	3.0 mphps (1.34 m/s^2)
Brake deceleration (full service)	3.0 mphps (1.34 m/s^2)
Emergency brake deceleration	5.0 mphps (2.25 m/s^2)
Maximum grade	9%
Vehicle width	8 ft (2.46 m)
Percentage low floor	50%
Number of seats (AW0)	29
Passenger capacity at AW3	155

IG has chosen a roof-mounted battery system as the primary component of its OESS concept with the following major characteristics of the SAFT BTR-515V-VL30P-SFP-052M:

- Lithium ion;
- Nominal voltage: 514.8 V;
- Capacity: 59 amp hr;
- Weight (total): 1,300 kg plus 200 kg control equipment.

In addition to two battery packs (one per truck), the battery system includes hardware for safety and monitoring, battery management, and power measurement. In Seattle's environment, it appears that there may not be a need for routine cooling of the battery, but heating will be necessary.

Project Schedule and Status

Fabrication started in late 2012, a combined propulsion system–OESS type of test was conducted in mid-2013, assembly and preliminary testing of the first car in the Czech Republic occurred in late 2013 through mid-2014, delivery of the first car to Seattle took place in late 2014, all four CZ cars were delivered by late spring 2015, and the three Seattle cars had final assembly by mid-2015. Qualification testing and commissioning of all seven cars are under way at the time of preparation of this paper. Opening for revenue service was planned for late 2015.

THE M-1 RAIL STREETCAR PROJECT: DETROIT

M-1 RAIL is a public-private venture in developing a streetcar system that will provide passenger service along the Woodward Avenue corridor, which extended approximately 3.3 mi (5.3 km) between Congress Street in the downtown business district at the southern end of the alignment and Grand Boulevard at the northern end of the alignment, a total of 6.6 mi (10.6 km) of revenue track. The route takes the streetcars around Campus Martius, a landmark park in the city of Detroit. There are 20 side and center load stations along the alignment, providing access to 12 locations. The streetcar will provide access to both Tiger Stadium and Ford Field, as well as other entertainment and shopping venues. In the near future, when the new Detroit Red Wings hockey arena opens, it will also be accessible by the streetcar. See Figure 12.

The BEC will supply six streetcars with off-wire operational capability. Delivery is expected to begin at the end of 2016. The streetcars will be 66 ft (20.1 m) long and 8 ft 8 1/2 in. (2.65 m) wide and be provided with lithium ion batteries to provide power when the streetcar is operating off wire [Dallas selected a car that is 8 ft (2.46 m) wide]. The streetcars will be

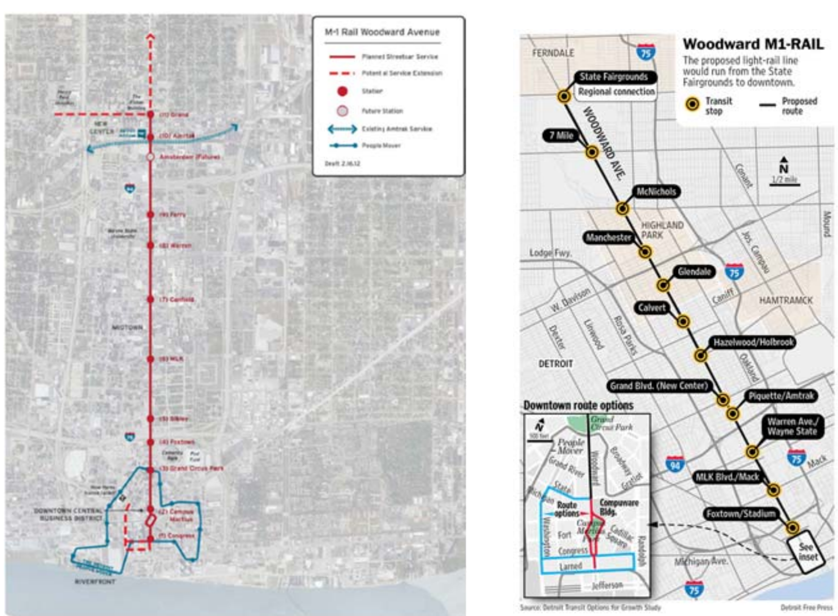

FIGURE 12 M-1 RAIL streetcar project: Detroit (*3*).

provided with the same equipment as was provided for the Dallas streetcar. M-1 RAIL's goal is to provide as much off-wire operation as possible, for among other reasons, to accommodate the Thanksgiving Day parade floats on Woodward Avenue. Much of the immediate downtown segment will be operated off wire. The vehicles will operate under wire for a portion of the middle segment of the alignment, and then the cars will operate off wire at the northern end where the alignment passes under the Amtrak overpass that crosses Woodward Avenue. The total off-wire distance will be approximately 50% of the line.

OKLAHOMA CITY MODERN STREETCAR PROJECT

A 4.6-mi (7.4 km) streetcar starter line in Oklahoma City, now in advanced planning, will bring rail transit to this major southern city. The project, currently estimated to cost $128.8 million, will circulate through the central business district, and will feature wireless operation beneath the BNSF Railway overpass linking the city's midtown area with the historic and adjoining Bricktown district. The project is currently evaluating the practicality of extending the off-wire segment to include a large portion of the north–south alignment. See Figure 13.

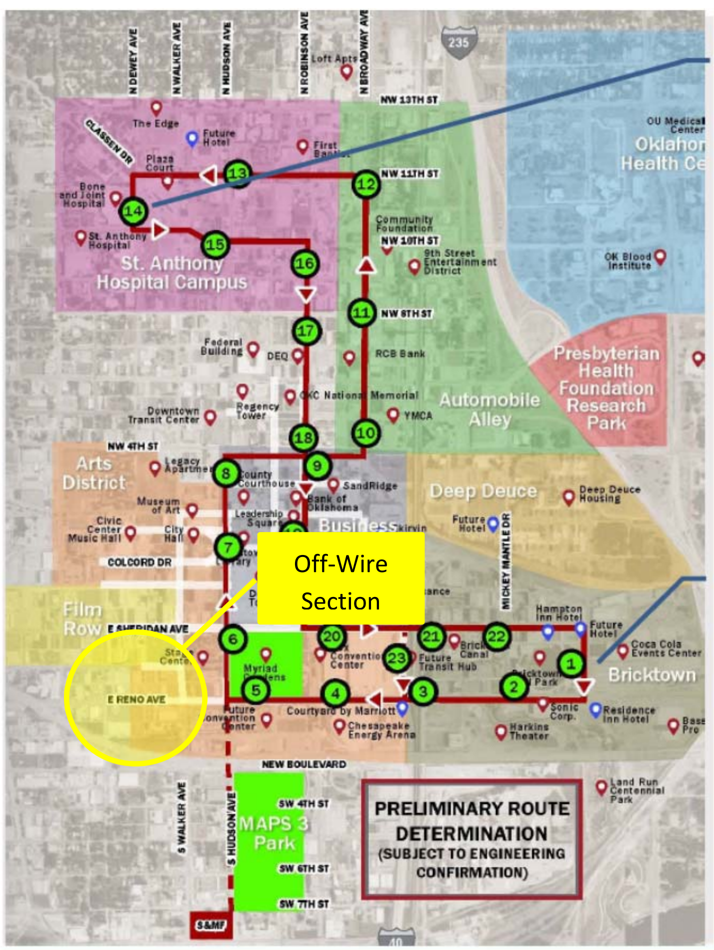

FIGURE 13 Oklahoma City Modern Streetcar project (5).

Opening is projected for late 2017 or early 2018 (*4*). The project includes an intermodal transit hub at the old Santa Fe Railroad station, a storage and maintenance facility, and an off-wire section as described above. The preliminary design was recently presented to the Oklahoma City Council (*5*). The following key status items were noted:

- Project budget: $129 million;
- Projected construction completion: Phase I, 2018; Phase II, 2021; and
- Streetcar contract (five vehicles) is under negotiation with Inekon.

CityLYNX GOLD LINE STREETCAR EXPANSION PROJECT: CHARLOTTE

The CityLYNX Gold Line is a 10-mi (16.1 km) streetcar system that will run east–west through uptown Charlotte. The alignment will provide dual track, mixed traffic operations through the entire length of the route, and will be constructed in three phases. Phase 1 opened in July 2015 with a 1.5 mi segment running from the Charlotte Transportation Center (CTC)/Arena on Trade Street to Novant Hospital at Hawthorne Lane and Fifth Street. Three historic Gomaco trolley cars operate in service on the Phase 1 route, which is powered entirely by an overhead contact wire system.

Phase 2 of the Gold Line will extend the system an additional 2.0 mi (3.2 km) west from the CTC to French Street and 0.5 mi (0.8 km) east from Fifth Street to Sunnyside Avenue. A fleet of six to eight modern streetcars will be procured to replace the existing fleet of Gomaco trolley cars to provide service on the combined line when the Phase 2 portion of the Gold Line is expected to open in late 2019. The Phase 2 portion of the line will include a 0.3-mi (0.5 km) off-wire segment from CTC/Arena to just west of Tryon Street. This off-wire segment will be situated in mixed traffic and includes a 6% grade over much of the off-wire distance between stations. Having no overhead wire in this segment of the Gold Line is critical to the City of Charlotte in order to maintain the aesthetics of the intersection at Trade and Tryon Streets, the heart of uptown.

Future expansions (Phase 3) will build out the route to a total distance of 10 mi (16.1 km) extending from the Rosa Parks Community Transit Center through the city center to the Eastland Community Transit Center, although a specific timeline has not yet been established.

Specifications for the modern streetcars with onboard energy storage are currently being prepared, and procurement of these cars was anticipated to begin in late 2015. See Figure 14.

DC STREETCAR PROJECT: WASHINGTON, D.C.

The Washington, D.C., streetcar system was developed on two separate alignments that will eventually be joined. The streetcar alignment that will be opened in the near future runs east–west from Union Station to 26th Street and Benning Road, a distance of approximately 2.0 mi (3.2 km). The alignment will run along H Street from Union Station to 12th Street (the start burst), turning southeast along Benning Road, and ending adjacent to the Car Barn and Training Center on 26th Street. The plan is to extend the alignment in the westerly direction along K Street, ending in Georgetown, and in the easterly direction toward Minnesota Avenue. During initial operations, the District DOT will operate six streetcars on its alignment. Three of the cars

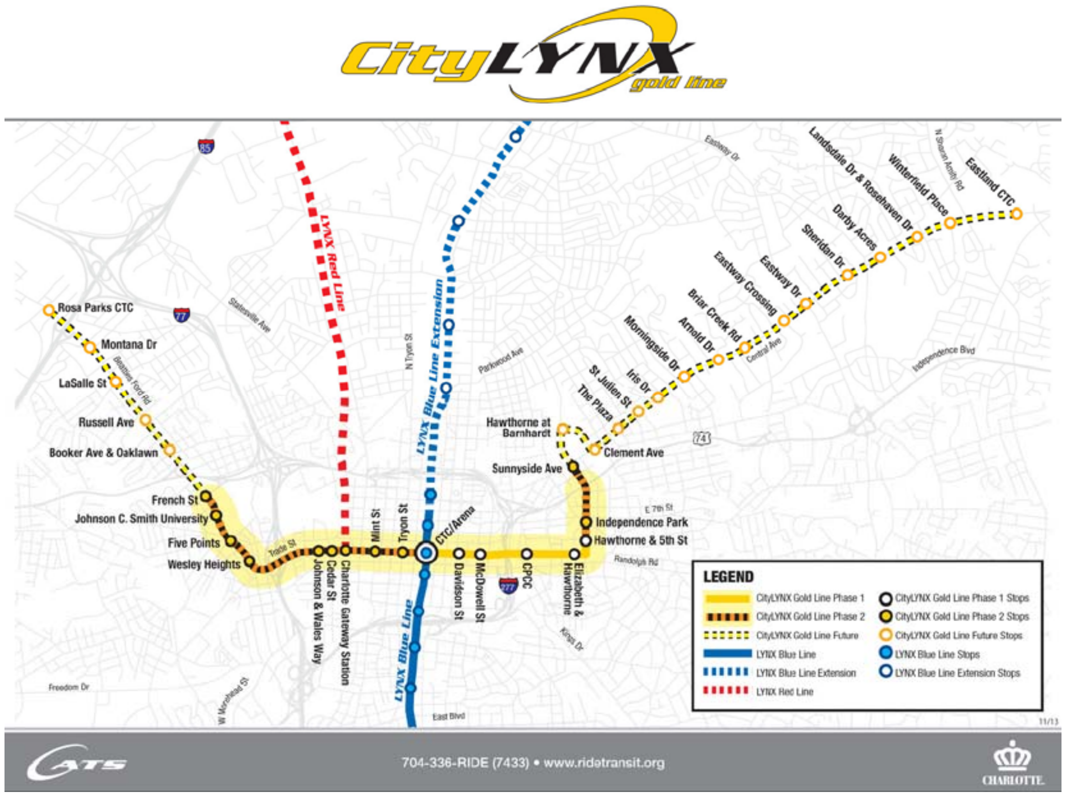

FIGURE 14 CityLYNX Gold Line streetcar expansion project (*6*).

were manufactured by Inekon, and three of the streetcars were manufactured by United Streetcar. All of the streetcars are on the property, and the District DOT expects to be in revenue operation by the end of 2015. The H Street corridor has seen considerable growth, both in commercial establishments and housing starts along the right-of-way, since work began on this alignment.

The streetcars are 66 ft (20 m) long and 8 ft (2.46 m) wide. The cars do not have off-wire capability with the exception of being able to move out of an intersection in the event of a loss of overhead power (rescue mode). The cars are similar to those cars provided to Portland, Seattle, and Tucson, Arizona, with the exception that the District DOT cars are provided with a load-leveling system to accommodate level passenger boarding for compliance with the Americans with Disabilities Act (low floor section). The cars are a combination high floor and low floor design with two biparting doors located in the low floor section and one single leaf door leading to the high floor section of the car. Future expansion of the system within the city will require off-wire operation, the details of which are still evolving. See Figure 15.

WAVE STREETCAR PROJECT: FORT LAUDERDALE

The South Florida Regional Transportation Authority (SFRTA), in conjunction with the Fort Lauderdale Downtown Development Authority and Broward County Transit, is developing the Wave Streetcar, a project that will provide service through downtown Fort Lauderdale north to Northwest 6th Street and south to 17th Street. Service is scheduled to operate 7 days per week, with headways of 7 1/2 min during peak service and 15 min during evening hours. See Figure 16.

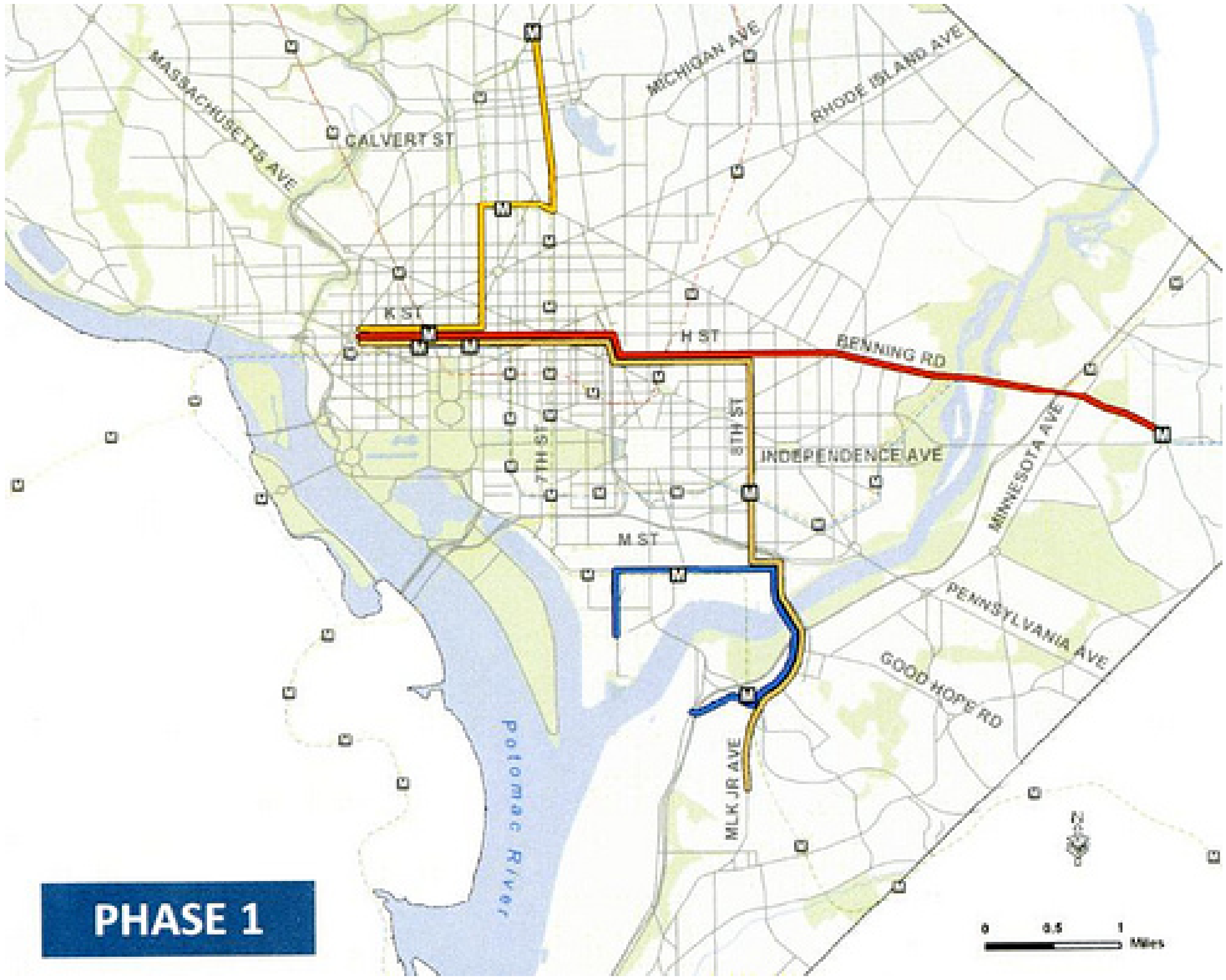

FIGURE 15 Streetcar Project: Washington, D.C. (*7*)

The system is planned to operate in mixed traffic on existing roadways with transit signal priority as an option. The alignment initially included a segment of off-wire operation to facilitate operating over the New River bascule bridge. The original plan was to operate off wire between the two stations on either side of the bridge. This segment has since been extended to operate off wire commencing at the second station on either side of the bridge, a distance of about 0.6 mi (0.9 km). The streetcars will therefore need to be equipped with an OESS to accommodate the needs of the Wave system. The initial order will include four streetcars with options for the procurement of additional vehicles to supplement service. See Figure 17.

As would be expected in Florida, the alignment is fairly flat, with the exception of the grades on the approaches to the New River Bridge where off-wire operation will be required.

The upcoming request for proposal will contain a requirement that SFRTA may purchase optional cars with additional car body sections, thereby providing additional passenger carrying capacity. The streetcars may be extended to a five-section configuration, rather than three. At present, SFRTA is in the process of developing its streetcar request for proposal and expects to advertise for procurement before the end of 2015.

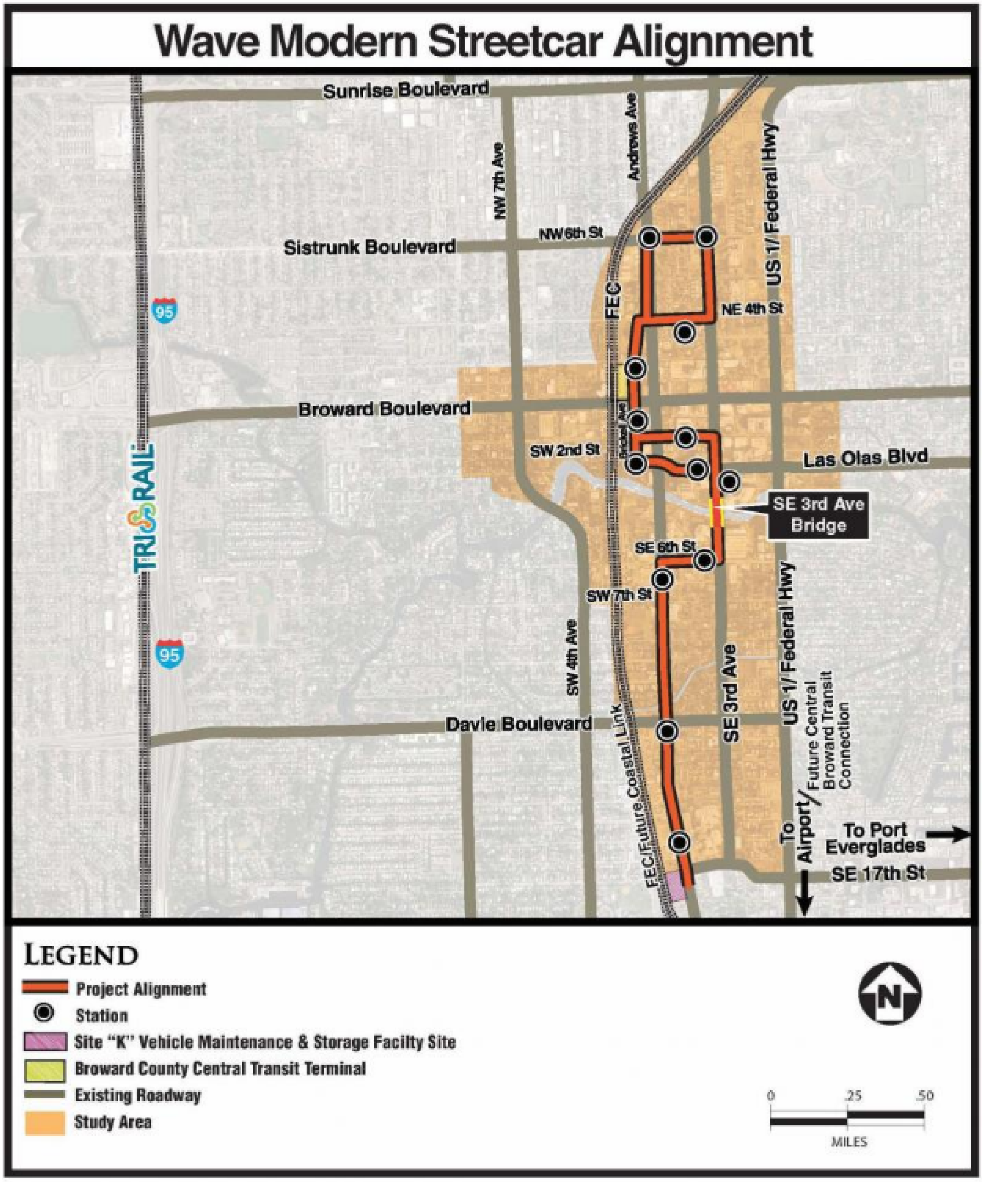

FIGURE 16 Wave Streetcar project: Fort Lauderdale (*8*).

CONCLUSION

Two streetcar lines with onboard energy storage systems were expected to be in revenue service in 2015. Four more are in advance stages of procurement with potentially more to follow in short order. The requirements for each application are unique, such that the solutions will vary, if not in technology, in sizing of the equipment. These requirements are based on the unique duty cycle in each application.

Off-wire solutions using onboard energy storage technology have arrived in North America, initially for streetcar applications. With the projects in operation and nearing completion, and those emerging, there will be a useful body of knowledge to guide similar applications on future projects. See Table 3.

FIGURE 17 New River Bridge on Southeast Third Avenue: Fort Lauderdale.

TABLE 3 Off-Wire Streetcar Summary

Location	Project	Route Length (mi/km)	Off-Wire Segment (mi/km)	Car Builder	OESS Tech.	Fleet Size	In-Service Date	Reasons for Off-Wire Segment
Dallas	Oak Cliff Streetcar	1.6/2.6	1.0/1.6	Brookville	Lithium ion batteries	2+2	April 2015	Historic bridge
Seattle	First Hill Streetcar	2.5/4.0	2.5/4.0	Inekon	Lithium ion batteries	7	Fall 2015	Trolleybus overhead wire interference, aesthetics, emergency recovery
Detroit	M-1 RAIL	3.3/5.3	~50% of the line in total	Brookville	Lithium ion batteries	6	Late 2016	Aesthetics, parade route, signature downtown park
Oklahoma City	MAPS 3 Modern Streetcar	4.5/7.2	TBD	Inekon (pending)	Lithium ion batteries?	5	Late 2017	Low clearance under overhead RR structures
Fort Lauderdale	Wave	2.7/4.3	0.6/0.9	TBD	TBD	4	Late 2017	Bascule lift bridge
Charlotte	CityLYNX Gold Line Phase 2	4.0/6.4	0.3/0.5	TBD	TBD	6–8	Late 2019	Aesthetics, signature downtown intersection
Washington, D.C.	DC Streetcar	TBD	TBD	TBD	TBD	TBD	TBD	Restriction on overhead wire in areas of the city

NOTE: Tech. = technology; MAPS 3 = Metropolitan Area Projects Plan 3; TBD = to be decided; RR = railroad.

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Ensuring LRT and Streetcar Safety

Getting a Safer LRT Through a Better Design of Its Insertion in Public Space

MARGARITA NOVALES
University of A Coruña

MANUEL TEIXEIRA
Mobility and Transport Independent Consultant Spain

The COST (European Cooperation in Science and Technology) Action TU1103, "Operation and Safety of Tramways in Interaction with Public Space," deals with the improvement of streetcar and light rail transit (LRT) safety through a better management and design of their insertion into urban spaces.

In Europe there are different approaches to the insertion of LRT systems. Some countries pay special attention to protection, with an approach closer to that of the heavy rail. Other countries try to get a more integrated system, with an easier coexistence with pedestrians and cyclists in the city center (an approach closer to that of streetcars) but still guaranteeing the capacity and adequate speed of the LRT when running through the metropolitan area.

In any case, even with the particularities of each country and/or network, LRT systems across the whole world deal with safety issues that are similar, and the solutions applied in some places can be extrapolated to other networks.

This paper presents some measures used by different LRT authorities in order to avoid crashes, and/or to improve the safety of their networks in some previous problematic points. The effectiveness of these measures is endorsed, when possible, by the figures about number of crashes in these locations by year before and after their implementation. These measures can be adopted by other authorities to solve similar problems, always considering the specific background of each network.

The origin of the main data presented in this paper is the hotspots' questionnaire made during the Action, which was filled in by 24 LRT agencies from all over Europe and Israel. The examples presented correspond to former hotspots, that is, locations that used to have the higher crash figures in the network but that are now safer places. Additionally to this source, another questionnaire about good and bad practices for interaction points design was made during the Action, gathering more than 130 examples. A very short summary of some of the conclusions obtained from this questionnaire is also included in this paper.

The COST Action TU1103, "Operation and Safety of Tramways in Interaction with Public Space," deals with the improvement of streetcar and LRT safety through a better management and design of their insertion into urban spaces. Thirty-four entities of 14 different European countries (plus Israel) have participated in the Action. Participants include LRT agencies, safety management entities and research bodies, and the UITP (International Association of Public Transport).

There are mainly two different parts of the LRT system that influence safety: the infrastructure and the management of its operation. The infrastructure is the more expensive part, and it is very hard to change once the system has been built. On the other hand, the operation management can solve some problems generated by poor infrastructure design, but this ability is limited and not applicable to every infrastructure problem.

The main safety issues that LRT systems face are related, in general, to the interaction with other street-users. This interaction is usually concentrated around the intersections with road vehicles (roundabouts and other at-grade intersections) and around pedestrian crossings or other points where pedestrians cross the LRT tracks. In this paper, several solutions to problematic points will be shown, some of them related to infrastructure improvements and others to operation management.

SAFETY AND LIGHT RAIL SYSTEM DESIGN

Three main concepts have to be considered in LRT design for guaranteeing safety: the visibility between the LRT and other street-users (road vehicles, pedestrians, and cyclists); the perception of the system (and information to other street-users); and the LRT protection in its interaction with them.

Visibility is an essential aspect for guaranteeing LRT safety. During the design of the layout, visibility has to be borne in mind from the beginning, in order to avoid subsequent problems. In general, the main considerations about visibility are

- For the case of visibility in road intersections, the best way of guaranteeing it is by making the intersection arms perpendicular between each other. Even if the existing streets were not perpendicular before the LRT implementation, sometimes the intersection can be transformed to a right-angled one with some slight modifications, if the space is available (see Figure 1*a* and *b*).
- On the other hand, both in intersections and in running sections, several aspects related to visibility have to be considered: the removal or movement, if possible, of elements that impair visibility between street-users and the light rail vehicle (LRV) (see Figure 1*a* and *b*); and the provision of adequate lighting conditions to guarantee visibility at night or in any other specific circumstances that can limit it.
- Additionally, it is important to bear in mind the visibility of signs and traffic lights. Measures for that can be the elimination, if possible, of elements that impair visibility of signs and traffic lights; the use of oversized signs in specific troublesome locations; the enlargement of red traffic light diameter; the use of brighter lights (e.g., LED), but considering the possible blinding effect, especially at night; and the use of a backboard behind traffic lights.

In any case, it is common to have some zones of the LRT network where visibility is poor due to the geometry of the tracks (sharp horizontal or vertical curves), to the streets layout (narrow streets), or to the existence of specific obstacles that cannot be removed or relocated. In those cases, the lack of enough visibility has to be mitigated by strengthening perception and protection measures.

On the other hand, visibility is specifically crucial when the LRV is present or approaching. Nevertheless, even when that is not the case, the other street-users have to be aware of the existence in the street of some zones that do not belong to them (but to the LRT). Raising this awareness is the objective of perception and information measures (whether the vehicle is present or not).

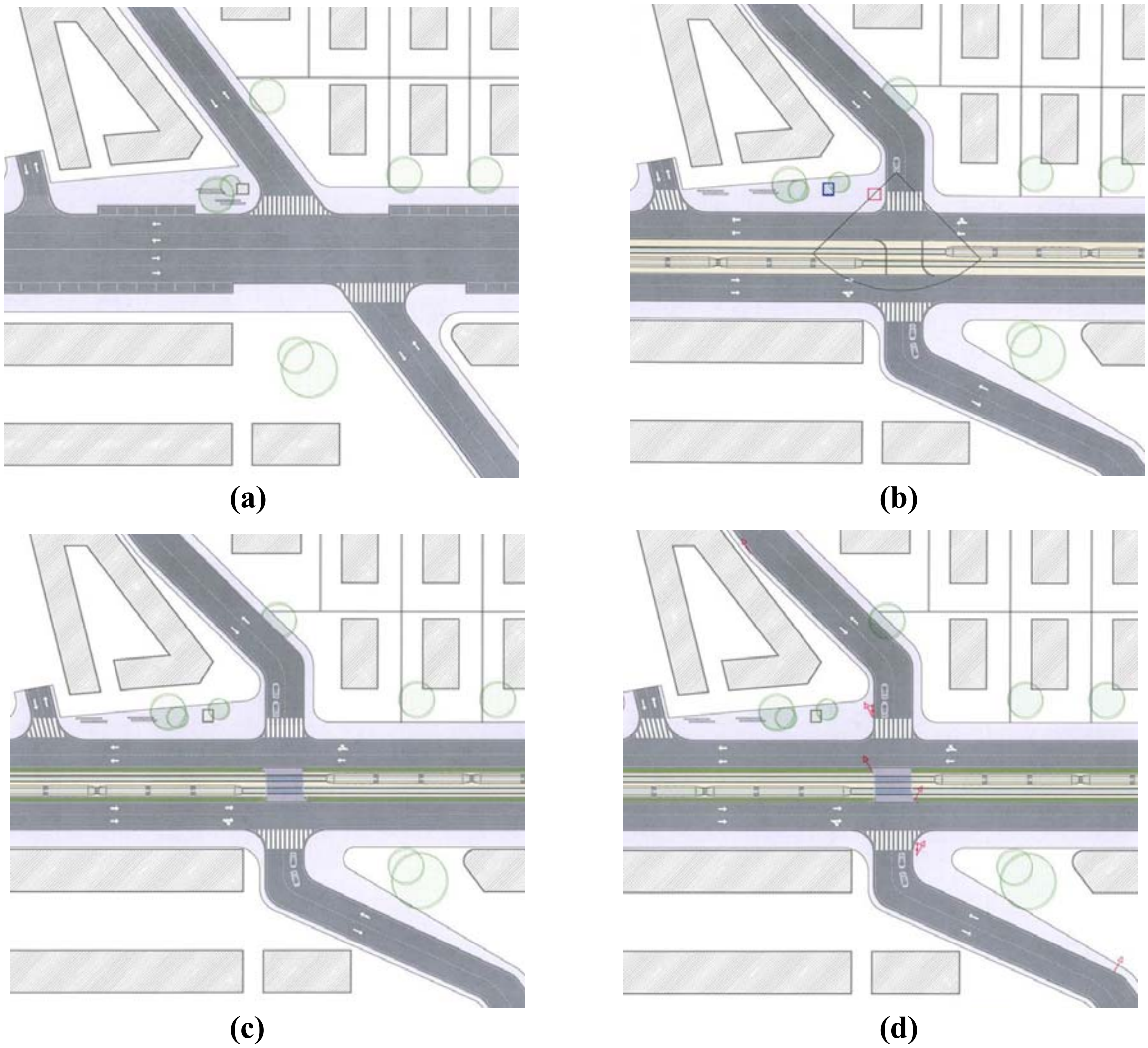

FIGURE 1 Measures for visibility, perception, and protection in relation to road vehicles in an LRT implementation: (*a*) condition of the intersection before the LRT implementation; (*b*) visibility—transformation of the existing nonperpendicular intersection into a right-angled one; elimination of visibility obstacles (green circles and change of obstacle from the red position to the blue one) and perception—LRT tracks paved in a different material or color than the adjacent lanes; (*c*) perception—clear identification of crossing zone by color contrast and protection—green (vegetal) separator; and (*d*) protection—vertical road signs (long- and short-distance signs) and traffic lights (when traffic lights do not work the vertical signs can prevent crashes).

Among measures related to perception, the more important ones in infrastructure design are finishing of the tracks with different material, color, or texture than the surrounding areas (see Figure 1, *b* and *c*) and marking the swept path of the vehicle. Measures related to perception in vehicle design are the use of bright colors on the LRVs, allowing a good identification in the cityscape; LRVs running with lights on; and the use of horns in specific points to announce that the vehicle is approaching.

For improving perception of the LRT system, several information measures can be used, like vertical and horizontal informative signs, as the ones addressed to pedestrians at pedestrian crossings (see Figure 2*a*).

Finally, the protection of the LRT system in relation to other street-users is also very important, both for assuring safety and for allowing LRVs to run at adequate speeds in some specific zones. Measures for protection can be physical barriers [for instance, separators from traffic lanes or fences and barriers for pedestrians; see examples in Figures 1*c* and 2*b* and additional ones in Novales et al. (*1*)], and prescriptive signs and traffic signals for road vehicle drivers (Figure 1*d*).

In Europe there are different approaches to the insertion of LRT systems. Some countries pay special attention to protection, using barriers and fences as the general way of inserting the LRT system, with a predomination of right-of-way of Category B (separated) and even Category A (controlled) (*2*), and with an approach closer to that of the heavy rail. Other countries try to get a more integrated system, with an easier coexistence with pedestrians and cyclists in the city center (an approach closer to that of streetcars), using in some stretches even Category C (shared) (*2*) but still guaranteeing the capacity and adequate speed of the LRT when running through the metropolitan area (mainly with Category B and sometimes Category A). Both styles provide adequate safety and can lead to good results, as long as citizens understand the priority rules and how they should behave in the surroundings of the LRT system. This understanding is very often determined by the history and tradition of streetcar and LRT systems in the country and by the existence (or not) of a national approach in the introduction of new systems.

In any case, even with the particularities of each country and/or network, LRT systems across the whole world deal with safety issues that are very similar, and the solutions and measures applied in some places can be useful for other networks facing similar problems or implementing a new line. This paper presents some solutions used by different LRT authorities in order to avoid crashes and/or to improve the safety of their networks in some previous problematic points. The effectiveness of these measures is endorsed, when possible, by the figures about number of crashes by year in these locations before and after their implementation. These measures can be adopted by other authorities to solve similar problems, always considering the specific background of each network.

(a) **(b)**

FIGURE 2 Measures for perception (information) and protection in relation to pedestrians in an LRT implementation: (*a*) perception (information)—pavement marking, and (*b*) protection—barriers (metallic and vegetal barrier).

METHODOLOGY

Thirty-four entities participate in the COST Action TU1103 from 15 different countries, including LRT agencies, safety management entities, and research bodies. UITP also takes part in the Action.

During the Action, a questionnaire was sent to several LRT agencies where they were asked to identify their main hotspots and former hotspots.

A total of 24 LRT agencies participated in the questionnaires, from 13 different countries: Austria (Vienna); Belgium (Brussels); Czech Republic (Brno, Prague, Olomouc); France (Le Mans, Lyon, Montpellier); Germany (Berlin, Bremen); Ireland (Dublin); Israel (Jerusalem); Italy (Milan); Netherlands (Amsterdam); Portugal (Lisbon, Porto); Spain (Barcelona, Bilbao, Tenerife); Switzerland (Bern, Geneva, Zürich); and the United Kingdom (Manchester, Sheffield).

The definition given for hotspots in the questionnaire was "the places in the urban area where the most accidents (collisions) occurred in a fixed period." Nevertheless, some of the agencies stated that they have a different way of defining hotspots. Former hotspots are locations that used to be hotspots in the past but are now safer places due to the measures implemented to improve the situation.

This paper presents a review of some of the former hotspots and measures applied by the different LRT agencies. The aim is that other LRT authorities facing similar problems or implementing a new line can use these examples as good practices for improving their systems. Where possible, figures about number of crashes by year before and after the implementation of the measures are included, in order to try to endorse their effectiveness.

Additionally to this source, another questionnaire about good and bad practices for interaction points design was made during the Action [see more detailed information in Novales et al. (*1*)], gathering more than 130 examples. A very short summary of some of the conclusions obtained from this questionnaire is also included in this paper.

FORMER HOTSPOTS AND BEST PRACTICES TO LEARN FROM

A total of 12 former hotspots and the measures applied for improving their condition is presented in this section. These hotspots are classified by the kind of interaction considered: road intersections (4 examples), roundabouts (5 examples), and interaction with pedestrians (3 examples). Additionally, in the last section of each point, supplementary information is included about some of the conclusions of the interaction points' questionnaire made during the Action.

Road At-Grade Intersections

Apart from the examples in this paper, several publications focus on LRT road intersections. As reference, several treatments for LRT road intersections where LRVs run at a speed higher than 55 km/h are presented in TCRP Report 69: *Light Rail Service: Pedestrian and Vehicular Safety* (*3*), and a discussion about signalization understanding is made in Pecheux and Golembiewski (*4*). On the other hand, several measures for improving left-turn intersections safety or for avoiding violation in prohibited left-turn locations are presented in TCRP Synthesis 79: *Light Rail Vehicle Collisions with Vehicles at Signalized Intersections* (*5*), Farrán (*6*), and Coifman and Bertini (*7*). Finally, hook-turn management of right-turns crossing LRT tracks in Australia is discussed in Currie and Reynolds (*8*).

Blackhall Place–Benburb Street Intersection, Dublin, Ireland

This is an intersection of a one-way street for road traffic with two-way LRT tracks on one side (Benburb), with a two-way street (Blackhall Place). The speed of the LRVs in this zone is 25 km/h. Several crashes occurred in this location due to red light infringements by road vehicle drivers. From 2009 on, several measures have been implemented (see Figure 3, *a*, *b*, and *c*):

- For improving visibility of signs: installation of oversized advanced LRT warning signs (900 mm) on both sides of the road intersection.
- For improving perception: installation of color contrasting pavement on the roads approaching to the intersection.
- For improving protection: installation of flashing red road studs (to display in conjunction with red traffic light) on both northbound and southbound carriageway approaches [a discussion about the effectiveness of this kind of solution in Houston, Texas, for avoiding red light running at LRT intersections is made in Tydlacka et al. (*9*)]; and implementation of high-friction, antiskid road pavement on both sides also.
- For reducing the chances of a crash happening even with road vehicle drivers' misbehavior, the LRVs are now obliged to come to a halt before crossing this road intersection. This is not a measure that can be used in an indiscriminate way as it reduces the commercial speed of the LRT system.
- A measure planned for the future for improving protection, which has been implemented in other intersections in Dublin, is the installation of red light cameras for photo enforcement of traffic lights obedience. This solution is used in Los Angeles as well (*3*).

Since the implementation of these measures (year 2009 on), crash figures seem to have improved slightly, although data are not conclusive. The number of crashes by year in this location follow: 2004: 3; 2005: 3; 2006: 2; 2007: 0; 2008: 2; 2009: 1; 2010: 4; 2011: 1; 2012: 1; 2013: 0; 2014: 2.

Bow Street Intersection, Dublin

This is a road intersection between a very narrow street (Bow) and another narrow street where only the LRT runs. Both the road traffic and LRT are controlled by signals. The solid timber hoarding on the right-hand side was causing intervisibility problems for the drivers of the LRVs and road vehicles, with the result of crashes due to road vehicle drivers not seeing the LRV and passing the traffic light at red.

As a measure to improve visibility, a section of the solid timber was replaced with a mesh-type fencing (see Figure 3, *d* and *e*).

On the other hand, for improving protection, the traffic signal sequence changed so that now it is always on red until the signal controller is activated by a road vehicle over the road signal loop. In this way, road vehicles always have to stop at this intersection as the road traffic signal is red. This improves the reaction time of road vehicle drivers, because they will always be moving into the intersection from a standing start.

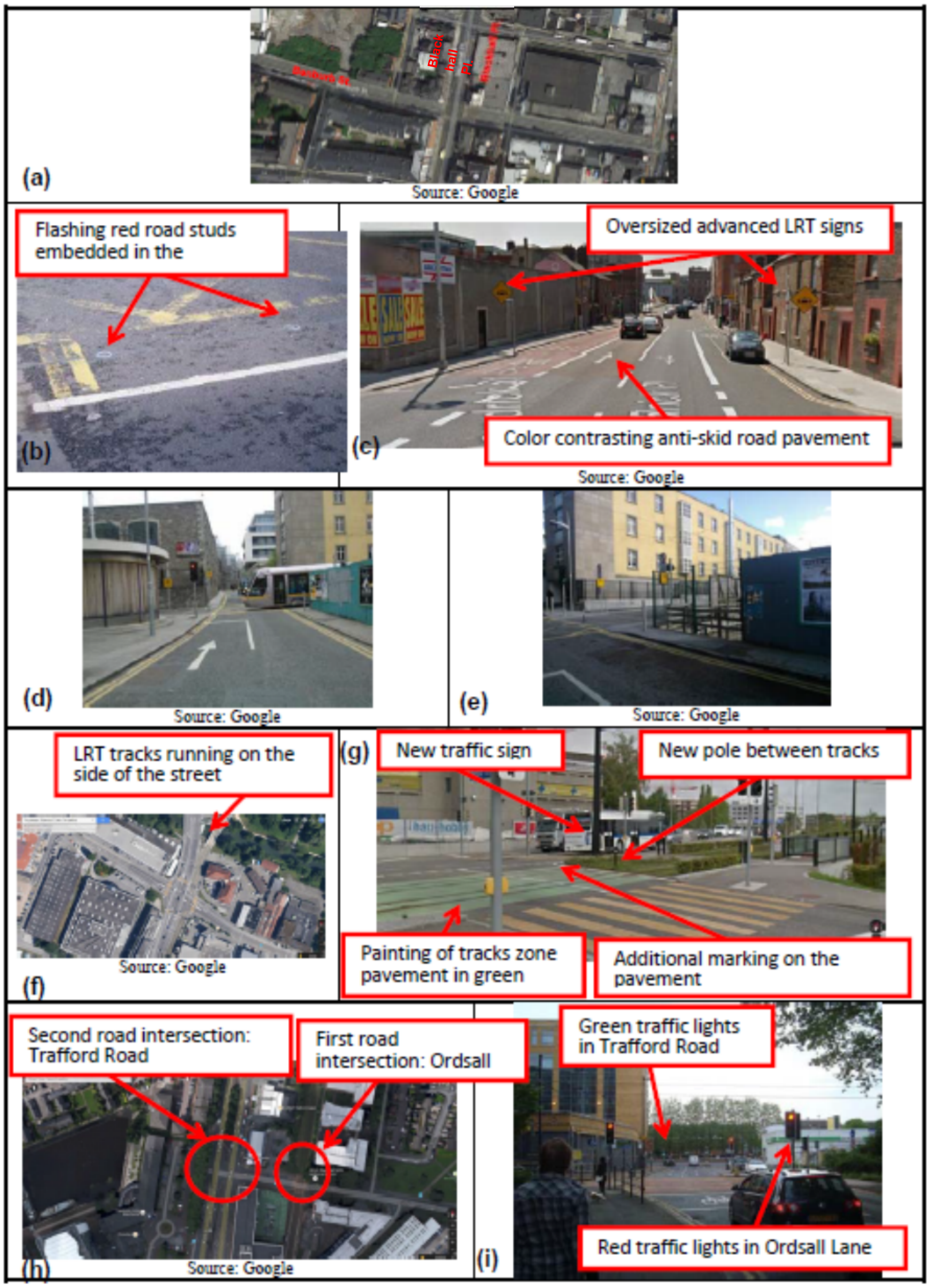

FIGURE 3 Road at-grade intersections. (*a*, *b*, and *c*) Blackhall Place–Benburb Street road intersection former hotspot: avoiding red light infringement: (*a*) location of the hotspot, (*b*) flashing red road studs embedded in the pavement, and (*c*) oversized advanced LRT warning signs and color contrasting antiskid road pavement. (*d* and *e*) Bow Street road intersection former hotspot: improvement of visibility by removing a wall: (*d*) before condition, and (*e*) after condition. (*f* and *g*) Ringstrasse in Dübendorf road intersection former hotspot: improvement of perception: (*f*) layout of the intersection, and (*g*) measures implemented. (*h* and *i*) Ordsall Lane–Exchange Quays road intersection former hotspot: improvement of protection: (*h*) layout of the intersection, and (*i*) "read through" problem between traffic lights.

Since the implementation of these measures (October 2012), crash figures seem to be slightly lower, although data are not conclusive. The number of crashes by year in this location follow: 2004: 0; 2005: 1; 2006: 0; 2007: 1; 2008: 1; 2009: 1; 2010: 0; 2011: 3; 2012: 1; 2013: 1; 2014: 0.

Ringstrasse in Dübendorf, Zürich, Switzerland

The problem in this case was the deficiency of perception in a road intersection of a new LRT line after the opening. The LRT tracks run on the side of the street (see Figure 3*f*), and the road vehicle drivers entering this street from the perpendicular one did not perceive the existence of the LRT tracks and got stuck in them (due to the green finishing in the first part and the slab track on the bridge). During the first three months after the inauguration, six events of this type occurred.

For reinforcing perception in this intersection, several measures were taken: the painting of additional marking on the pavement; the disposition of a new traffic sign indicating the correct way for road vehicles; the installation of a pole between the tracks; and, finally, later, the painting of the tracks zone pavement in green (see Figure 3*g*). Thanks to these measures, invasion of the tracks zone has been eradicated in this intersection.

Ordsall Lane–Exchange Quays Road Intersection, Manchester, United Kingdom

In this case, there are two very close intersections (around 70 meters apart), both of them controlled by traffic lights (see Figure 3, *h* and *i*). Sometimes drivers stopped at the Ordsall Lane intersection "read through" the intersection to the Trafford Road signals, that is, they see that the Trafford Road signals are green and assume they are clear to proceed across the LRT intersection. Between 2003 and 2013 there were 14 incidents of this type. The solution implemented was improving protection by fitting the Trafford Road intersection traffic lights with louvers that avoid the "read through" problem. In this way, drivers can see only the red/green aspect of these signals when they are close to them.

The problem seems to have improved since the implementation of this measure.

Other Measures for Improving At-Grade Intersections' Safety

Some of the measures mentioned for road intersections in the interaction points' questionnaire, apart from the ones presented previously, were

- For improving visibility in the case of left turns: design of the left turn perpendicularly to the LRT tracks. For that, a green space between the turning lane and the tracks is introduced to allow road vehicle drivers to make the turn before crossing the LRT tracks, encountering them in a perpendicular direction, and being able to see if there is an LRV arriving to the intersection [see Novales et al. (*1*)]. This measure can only be implemented if the needed space is available.
- For improving perception and protection: implementing in road lanes a smooth ramp right before achieving the intersection in order to reach the track (at a slightly higher level) and also to increase driver awareness and reduce road vehicle speed; reinforcing traffic lights by including an active LRV symbol that starts blinking when the LRV is approaching; making the

left or right turns over the tracks physically impossible or very difficult [see Novales et al. (*1*)]; and using traffic barriers (red and white stripes) connected with traffic lights message and LRV presence (only in especially troublesome locations).

Roundabouts

In general, when a new LRT is introduced on a roundabout, the LRT runs through the roundabout's center and the roundabout management changes. The roundabout works as a conventional one when LRVs are not present, but traffic lights are provided in the points where the ringroad crosses the tracks, to give LRVs priority when they approach the roundabout (*1*). For avoiding events in this kind of configuration, in addition to provide the adequate visibility, perception and protection need to be reinforced (as will be shown in the next examples).

The French perspective on LRT roundabouts is presented in the French recommendation [see CERTU (*10*)].

Paul Cézanne Roundabout, Le Mans, France

Le Mans LRT was inaugurated in November 2007. The LRT runs through the center of Paul Cézanne roundabout, and several crashes occurred with road vehicles that did not respect traffic lights (and LRVs priority) as well as passengers' falls due to emergency braking as a consequence of that.

The measures applied to deal with this problem were the following (see Figure 4*a*, *b*, and *c*):

- Improving perception by using "shark teeth" marks in the points where the roundabout's ringroad crosses the LRT tracks, implemented in September 2010.
- Improving protection by implanting a second R24 traffic light, blinking alternatively with the existing one (flip-flop), implanted in May 2012.

The evolution of the number of incidents (crashes and passengers' falls) in this point is the following: November 2007 to end of 2008: 7; 2009: 2; 2010: 0; 2011: 1; 2012: 2; 2013: 0. The sharp reduction after the beginning of operation is quite common after the implementation of new LRT networks as the other street-users need a learning time to know how to interact with the new system. In any case, it seems that there has been a slight improvement due to the measures implemented, although data are not conclusive.

São Brás Roundabout, Porto, Portugal

Again, in this case, the new LRT line runs through the center of the São Brás roundabout, and several crashes happened because of the disrespect of red traffic lights by road vehicle drivers (four crashes in 1 year).

The measures applied to improve the situation were, in this case (see Figure 4*d*, *e*, and *f*):

- Improving the visibility of traffic lights by relocation of some signs that were causing confusion, and by increasing the diameter of traffic lights to get better awareness by road vehicle drivers.
- Improving perception by painting new stopping lines on the pavement.

(a)

(b)

(c)

(d)

(e)

FIGURE 4 Roundabouts. Paul Cézanne roundabout former hotspot: (*a*) layout of the Paul Cézanne roundabout; (*b*) Paul Cézanne roundabout before condition; and (*c*) Paul Cézanne roundabout after condition. São Brás roundabout former hotspot: (*d*) initial condition of the São Brás roundabout; and (*e*) current condition of the São Brás roundabout with new stopping lines painted on the pavement.

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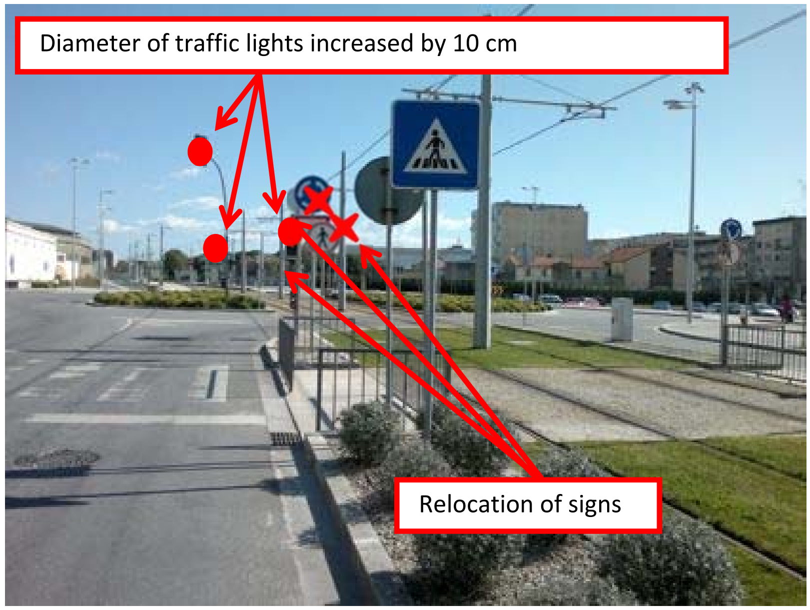
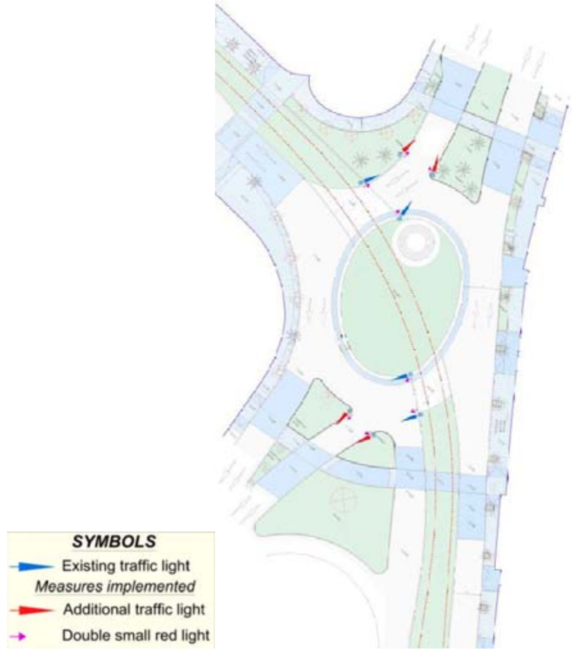


(f)

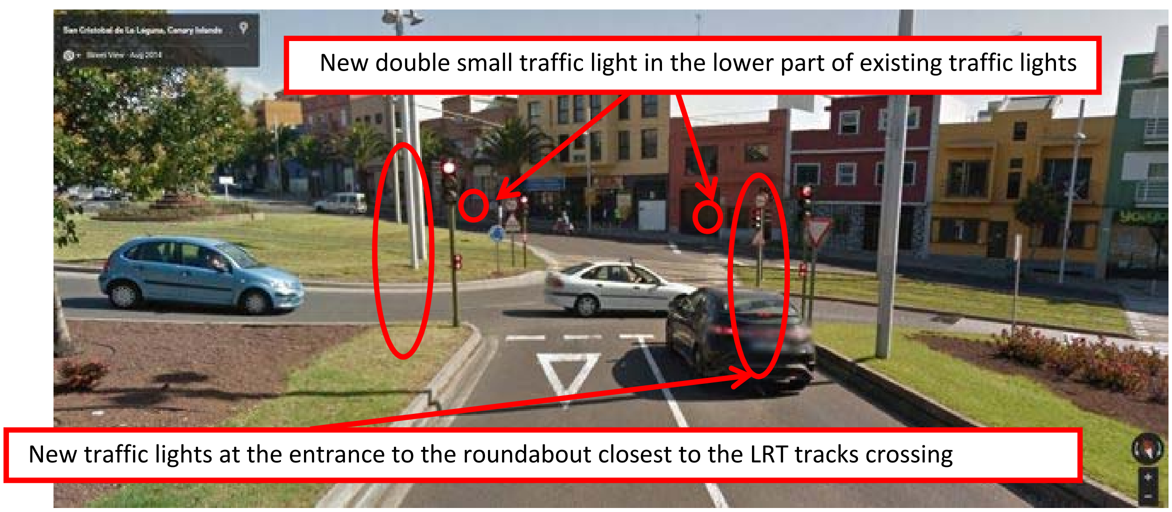
(g)

(h)

FIGURE 4 (*continued*) **Roundabouts. (*f*) measures applied in the São Brás roundabout entrance. (*g* and *h*) Cruz de Piedra roundabout former hotspot: (*g*) Cruz de Piedra roundabout layout; and (*h*) road safety campaign at Cruz de Piedra roundabout.** (*Continued on next page.*)



(i)



(j)

FIGURE 4 (*continued*) Roundabouts. Cruz de Piedra roundabout former hotspot: (*i*) sketch of the measures applied (traffic lights) at Cruz de Piedra roundabout; and (*j*) photo of the measures applied (traffic lights) at Cruz de Piedra roundabout.

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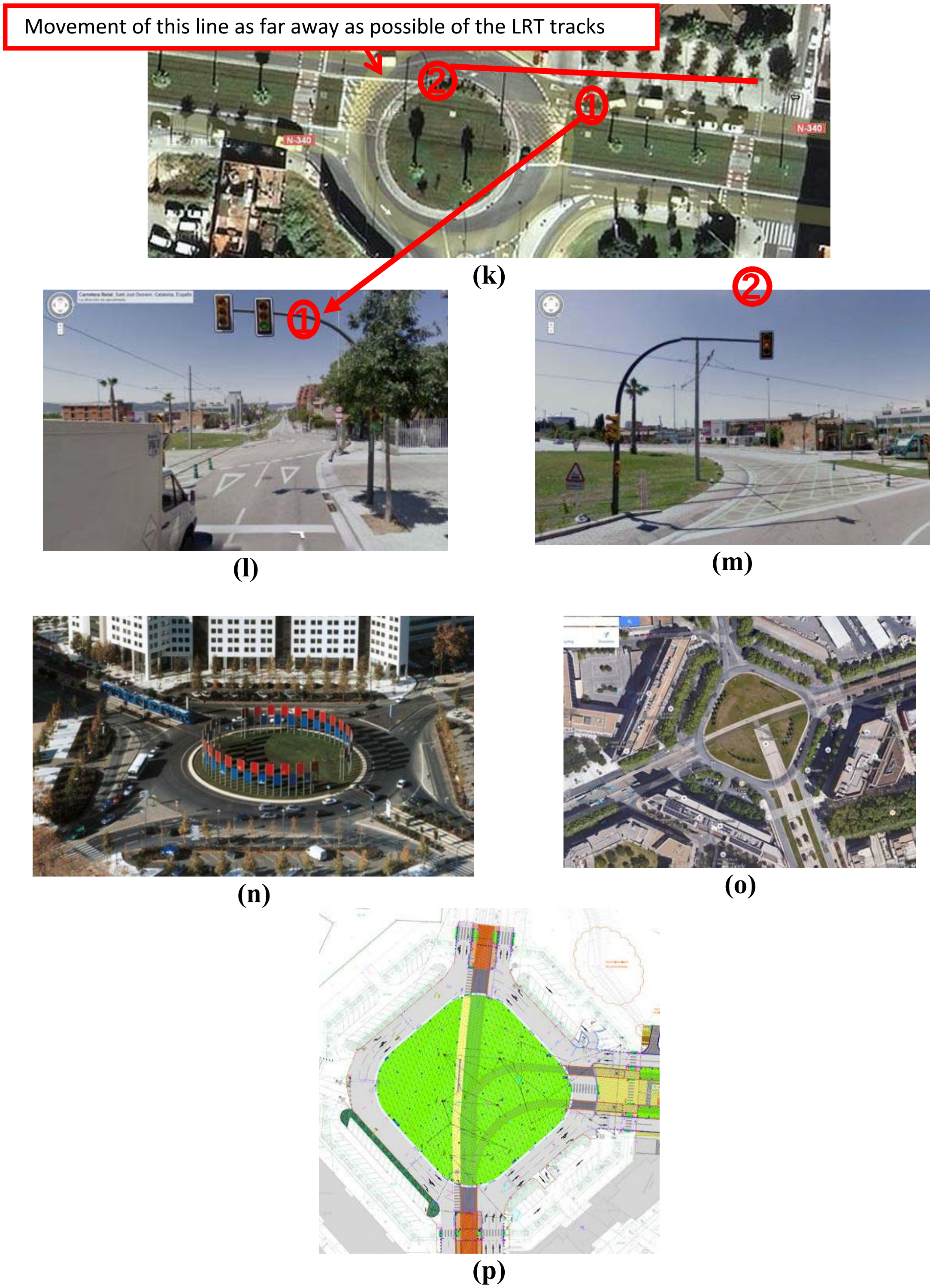

FIGURE 4 (*continued*) **Roundabouts. (*k*, *l*, and *m*) Reial Road–Baix Lobregat Avenue roundabout former hotspot: (*k*) roundabout layout, (*l*) stopping line relocation, and (*m*) traffic lights situation. (*n*, *o*, and *p*) Ernest Granier roundabout former hotspot: (*n*) initial condition of the roundabout, (*o*) current condition as a conventional intersection with rhomboid shape, and (*p*) sketch of the current condition of the intersection.**

Cruz de Piedra Roundabout, Tenerife, Spain

The first line of the Tenerife LRT was inaugurated in June 2007. Cruz de Piedra is another roundabout with the LRT tracks running through its centre. In this case, as it is shown in Figure 4*g*, two of the road entrances to the roundabout are very close to the points where the ring road crosses the LRT tracks. This leads to a complicated situation, as road vehicle drivers have to focus on the road vehicles coming from the left in the ring road but immediately change their attention to the traffic lights that protect the crossing over the LRT tracks (and to the LRVs coming either from the right or from the left).

Several crashes took place caused by drivers ignoring red lights. The measures applied (in November 2007) were focused on improving protection, as follows (see Figure 4*i* and *j*):

- Duplication of traffic lights on the edge of the LRT tracks: A new double small traffic light is provided in the lower part of existing traffic lights (at drivers' eyes height) to reinforce the awareness of road vehicle drivers arriving to the intersection.
- New traffic lights have been provided at the entrances to the roundabout that are close to the LRT tracks crossing.

Additionally, a road safety campaign was performed distributing leaflets to road vehicle drivers that reminded them about road safety rules (see Figure 4*h*). Even a TV program about road safety was sponsored.

The evolution of the number of crashes and of the number of emergency brakes (in brackets) in this location is the following: June to end of 2007: 9 (64); 2008: 7 (24); 2009: 4 (29); 2010: 2 (14); 2011: 1 (9); 2012: 0 (11); 2013: 3 (12). Again, in this case the reduction can be due to the learning time of other street-users, as mentioned before. In any case, it seems that there has been a slight improvement due to the measures implemented, although data are not conclusive.

Reial Road–Baix Lobregat Avenue Roundabout, Barcelona, Spain

In this case, the LRT crosses the roundabout off center (see Figure 4*k*, *l*, and *m*), generating a situation similar to a left turn with visibility problems. The roundabout leads directly to a highway, and the traffic flow is high. There were several crashes because road vehicle drivers had a green light for entering the roundabout (traffic light 1) but then they found a red light for crossing the LRT tracks (traffic light 2). The green light 1 is thought for those road vehicles who want to continue straight-on, but the consequence is that many drivers that wanted to turn left entered in the roundabout and they did not expect to see a red light 2, as in roundabouts without LRT the road vehicle always has the priority once it has entered the roundabout.

The measures applied (during year 2007) were as follows (see Figure 4*k*, *l*, and *m*):

- Improving perception (and allowing for a longer reaction time in case of a risky situation) by moving away the stopping line as far away as possible from the LRT tracks.
- Improving protection by changing the traffic lights' cycle, implementing red lights for the entrance to the roundabout whenever the LRV is approaching. This measure has the inconvenience of worsening road traffic flow and can lead to higher levels of congestion.

The evolution of the number of crashes in this location is the following: Year 2006: 10 crashes; 2007: 8; 2010: 1; 2011: 2; 2012: 3; 2013: 1. It seems that there has been an improvement due to the measures implemented.

Ernest Granier Roundabout, Montpellier, France

Line 1 of Montpellier LRT ran through the center of this roundabout at a maximum speed of 40 km/h. Several events took place due to the disregard of traffic lights by road vehicle drivers, with a total number of 23 from 2000 to 2009 (with four events in 2009, four in 2008, and five in 2007).

The solution to this problematic point was related to the construction of the new line 3 (in 2010), linked to line 1 at the center of the roundabout. Due to the installation of the switch devices for this connection, the speed of LRVs running through this zone lowered to 15 km/h. In addition, the operation of the whole intersection changed: It became a conventional road intersection (although with a rhomboid shape) with unique direction, two lanes (plus one for right turns), and a management of conflicts between LRVs and road vehicles and road vehicles between each other by traffic lights at each intersection.

These changes led to the absence of events since 2009. It is important to note that it was an expensive solution and that the speed reduction for LRVs has consequences in the quality of service. On the other hand, due to the change of the intersection configuration at the same time of the speed reduction, the effects of each measure by itself cannot be determined.

Other Measures for Improving Roundabout Safety

Some of the measures mentioned for improving perception for roundabouts in the interaction points' questionnaire, apart from the ones presented previously, were

- Marking the central island and the ringroad in different colors and highlighting the existence of the tracks and the swept path by different colors or materials; and
- Providing informative signs at the roundabouts' entrances of LRT tracks crossing the roundabout.

Interaction with Pedestrians

Some of the publications treating pedestrians' safety around LRT tracks are *TCRP Report 69*: *Light Rail Service: Pedestrian and Vehicular Safety* (*3*), *TCRP Report 137*: *Improving Pedestrian and Motorist Safety Along Light Rail Alignments* (*11*), and Currie and Reynolds (*12*).

Ribera Street, Bilbao, Spain

Ribera Street is located in Bilbao city center. In this street, the LRT runs adjacent to the sidewalk that is located under the arcade of the building (see Figure 5*b*). The pillars of the arcade lead to a visibility problem between LRVs and pedestrians, and this fact combined with the crossing of the tracks by pedestrians out of pedestrian crossings make this zone of the LRT line a dangerous one.

(a)

(b)

(c)

(d)

(e)

FIGURE 5 Interaction with pedestrians. (*a*, *b*, *c*, and *d*) Ribera Street former hotspot: improvement of safety by installing light signals embedded in the pavement: (*a*) Bilbao LRT line sketch; (*b*) view of the LRT tracks adjacent to the arcade; and (*c* and *d*) light signals embedded in the pavement. (*e*) Pantheonlaan Street former hotspot: (*e*) before condition. (*Continued on next page.*)

(f)

(g)

(h)

(i)

FIGURE 5 (*continued*) **Interaction with pedestrians. (*f* and *g*) Pantheonlaan Street former hotspot, after condition: barriers and sign with information for pedestrians about LRVs priority. (*h* and *i*) Zara and Testi Avenues former hotspot: (*h*) Before condition, and (*i*) After condition: pedestrians face the LRV approaching direction before crossing.**

As the visibility problem could not be addressed without an important investment in the relocation of the tracks, the measures to be applied in this case, for protection, could be the disposition of fences for pedestrians or the improvement of protection by means of active warning measures. In this case, the second option was selected, installing light signals embedded in the pavement that blink when an LRV is approaching (see Figure 5*c* and *d*).

These signals were installed in June 2009. The number of crashes with pedestrians has decreased since then, being as follows: Year 2008: 14 crashes; 2009: 13; 2010: 12; 2011: 10; 2012: 6; and 2013: 5.

Pantheonlaan Street, Brussels, Belgium

In this zone, the LRT tracks run adjacent to a popular park with lots of visitors. Trees impair visibility (see Figure 5, *e*, *f*, and *g*), and visibility at night is also poor. Pedestrians cross the tracks outside of the pedestrian crossing. Additionally, as the pedestrian crossing was too wide sometimes it was unlawfully used by service vehicles entering and exiting the park.

The option of removing trees for addressing the visibility problem was not adequate, so the measures for improving safety in this case were focused on improving perception (information) and protection. In relation to information, at each pedestrian crossing, signs were added to remind pedestrians that priority should be given to the LRVs. Additionally, LRVs have been equipped with LED lights to improve perception at night. In relation to protection, fences have been located over the whole length to force pedestrians to use the designated crossings. At the crossings, the barriers are placed in such a way that service vehicles can no longer use them to enter the park. In this case, it was hard to obtain permission to place the barriers.

Zara and Testi Avenues, Milan, Italy

The LRT runs on the lateral part of these wide avenues adjacent to a green zone on one side and to a service lane on the other. These avenues are the most important way to get into the city center from the north. There were problems with pedestrians who crossed the intersection on the pedestrian crossing without checking if an LRV is approaching.

The layout of the more problematic pedestrian crossings have been changed to improve perception, creating paths that force pedestrians to face the approaching LRVs before crossing (see Figure 5*h* and 5*i*). This measure is similar to the solution proposed in Figure 8C-9 of *The Manual on Uniform Traffic Control Devices for Streets and Highways* (*13*).

Note in the figure that zebra marks are painted on the pedestrian crossing over LRT tracks in this case. This is not the general solution in every European country, as the zebra denotes priority to pedestrians, while in most of the European countries LRT has priority over them.

Other Measures for Improving Pedestrian Crossings' Safety

Some of the measures mentioned for pedestrian crossings in the interaction points' questionnaire, apart from the ones presented previously, were

- For improving perception: Designate in a proper way the adequate places for pedestrians to cross the LRT tracks, by means of passive warning measures as markings in the pavement, pavement texture and colors differentiation (*1*), or by means of informative vertical signs indicating the presence of the LRT tracks (*1*).
- For improving protection: Use passive prescriptive measures, like vertical signs forbidding the crossing of the line; use active warning measures like flashing lights or signs, LED lights embedded in the pavement repeating the message of traffic lights (*1*), or acoustic signals; use uncomfortable pavement in the LRT tracks, except in the designated crossing.

CONCLUSIONS

This paper presents some of the former LRT hotspots whose information has been collected in the questionnaire made during COST Action TU 1103 "Operation and Safety of Tramways in Interaction with Public Space." Twenty-four LRT agencies participated in this questionnaire. Former hotspots are locations that used to have the higher crash figures in the network but that are now safer places. For each former hotspot presented, the measures implemented for improving the situation have been detailed, which can be adopted by other authorities to solve similar problems, always considering the specific background of each network.

When possible, figures about number of crashes by year before and after the implementation of the measures in the location have been included to try to endorse their effectiveness. Nevertheless, it is fair to say that, in general, the improvements in these figures are slight (because fortunately the number of LRT crashes is commonly low). On the other hand, many factors can influence the situation (as road traffic flow changes, new speed limitations, or others) in such a way that it is difficult to infer if the measures have been effective or not.

Additionally to the hotspots' questionnaire, another questionnaire about good and bad practices for interaction points design was made during the Action, gathering more than 130 examples. A very short summary of some of the conclusions obtained from this questionnaire is also included in this paper.

A thorough analysis of all the information gathered in the COST Action has been made, that has been summarized in the final report, which is available in the Action website (http://www.tram-urban-safety.eu/). There is a specific section of the report focused on hazards faced in each kind of interaction point, and measures to avoid these hazards, with many real examples, which can be interesting for readers of this paper.

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Advancing Safety Rules Compliance

Proactive Management Through Simplified Data Analysis

KIMIYA AGHEVLI
BRIAN DWYER
JOHN GASPARINE
STV Inc.

MICHAEL WIEDECKER
Maryland Transit Administration

Many recent accidents in the transit industry have been attributed to safety rule violations. However, the extent to which operators abide by these rules is generally evaluated retrospectively after an accident, inhibiting an agency's ability to proactively address concerns to prevent incidents. Historically, agencies have used efficiency checks to verify that operators follow safety-critical rules, ensure a management field presence, and reinstruct employees if a violation is observed; however, this approach focuses on individuals and does not proactively identify overarching safety trends.

In 2010 the American Public Transportation Association (APTA) Operating Standards Committee established its Rules Compliance Standard, which provided core criteria for rules compliance programs. In 2011, *TCRP Report 149: Improving Safety-Related Rules Compliance in the Public Transportation Industry* offered best practices for agencies to develop or improve upon existing rules compliance programs. In 2012 the Maryland Transit Administration (MTA) reviewed these best practices and peer programs in the industry to commence developing their Safety Rules Compliance Program (SRCP). In 2013 the MTA convened a cross-functional team comprising leaders from the Office of Safety, core operating modes, Central Control, Operations Training, and representatives from the State Safety Oversight Agency (SSOA) to develop its SRCP.

MTA redefined SRCP best practices, building upon a foundation of industry best practices and a comprehensive project management approach. Unique program features include shared departmental responsibility, tiered staff structure, targeted observation schedules, and user-friendly software that provides comprehensive analysis. The MTA program's tangible benefits include improving compliance rates, targeting location-specific issues, identifying high-risk employees, and increasing departments' focus on safety.

THE PROBLEM

"Do my operators always abide by signal aspects and comply with instructions provided at flagging sites on the ROW?" "Do my operators always obey the speed limit?" These are basic questions that have serious implications for the safety of a transit system, yet most transit agencies cannot answer these questions with confidence, let alone quantify the degree to which their employees comply with safety-critical rules. Many of our nation's transit accidents are preventable, stemming from rule violations.

In 2008 a Metrolink Commuter Train and Union Pacific freight train collided head-on due to the Metrolink operator running through a red signal while thought to be using a cell phone; 135 people were injured and 25 died. In 2013 a Metro North Commuter Train derailed on a curve due to the operator traveling at almost three times the speed limit; 61 people were injured and four died. Two years later, in May 2015, an Amtrak train derailed outside Philadelphia, traveling over 100 mph on a 50-mph curve, injuring more than 200 and killing eight people. Since 2012 the industry has seen a surge in railroad worker deaths, leading to a special investigation report from the National Transportation Safety Board, which detailed 14 accidents that resulted in 15 roadway workers' deaths in 1 year (*1*).

These stories are far too common, and they are not constrained to commuter rail either. While heavy rail, light rail, bus, and paratransit accidents statistically result in fewer injuries and fatalities, they occur more frequently; and many of these accidents are preventable. In response to these incidents, the industry has progressively developed a number of methods for proactive field evaluation of employees' rule compliance, which ultimately creates opportunities for managerial intervention.

PREVIOUS RESPONSES TO THIS PROBLEM

For years, transit properties have employed "efficiency checks" to help verify that employees follow safety-critical rules. These efficiency checks helped ensure a management staff field presence and provided an intervention opportunity if a rule violation was observed; however, efficiency checks evaluate safety on an individual basis without identifying overarching trends.

APTA's Operating Standards Committee established a rules compliance program standard in 2010. This standard, APTA RT-OP-S-011-10–Rule Compliance (*2*), defines the general requirements of a rules compliance program and outlines the key considerations for transit properties to "define the rule compliance requirements to verify and evaluate that its rules are followed." The standard presents nine components necessary to establish a basic rules compliance program:

1. Evaluation process to identify which rules and procedures will be part of the program.
2. Position or function the program will evaluate.
3. Organizational responsibility delegated for administering the rule compliance process.
4. Evaluation cycle or the frequency of compliance checks.
5. Method of verification to ensure the program collects data in a methodical, objective manner.
6. Record-keeping from compliance observations, data analysis, and corrective actions.
7. Correction actions taken in response to address problems the program identifies.
8. Metrics that measure baseline levels and track changes over time to assess effectiveness.
9. Validation process to assess the effectiveness of corrective actions.

The Transit Cooperative Research Program released *TCRP Report 149*: *Improving Safety-Related Rules Compliance in the Public Transportation Industry* (*3*) as a resource for the public transportation industry. The report presented best practices and ideas for transit agencies to develop or improve existing rules compliance programs.

Several transit agencies have used APTA RT-OP-S-011-10 and TCRP Report 149 as guides to develop and enhance their rules compliance programs. MBTA, the Southeastern Pennsylvania Transportation Authority (SEPTA), the New Jersey Transit (NJT), and the Santa Clara Valley Transportation Authority (VTA), among others, have formal simple railroad command protocols in place that they use to drive management decisions.

MTA'S RESPONSE TO THIS PROBLEM

As with many transit properties, the MTA has experienced its share of preventable accidents and incidents. While it has always maintained standard operating procedures for efficiency checks, the MTA decided to develop a formal SRCP (program) in an effort to more proactively manage system safety following an unprecedented rise in derailments and switch run-throughs in light rail operations. In December 2012 the MTA reviewed APTA RT-OP-S-011-10 and TRCP Report 149 and also conducted a peer survey to identify additional SRCP best practices.

In March 2013 the MTA convened a cross-functional team to commence developing its SRCP. The team comprised leaders from the Office of Safety, the core operating modes, central control, operations training, representatives from the SSOA, and private industry. This team set out to redefine SRCP best practices, meeting every two weeks over the course of 5 months to rapidly develop a pilot SRCP.

The initial pilot was launched in the MTA Metro (heavy rail) mode in September 2013. Since then, the SRCP has expanded to include the bus and light rail modes as well. The MTA has built a number of features into its SRCP to enhance its function and ease of use, and ultimately enable implementation with existing in-house resources.

Tiered SRCP Management Staff Ensures Effective Communication and Implementation

Staff is involved in the program both laterally across departments as well as vertically throughout management levels, which reinforces a culture of safety throughout MTA's operations. Three distinct but interdependent groups of MTA personnel are responsible for administering the SRCP.

1. The Safety Management Committee governs the program and is ultimately responsible for all approvals and modifications.
2. Departmental testing coordinators act as liaisons between the committee and rules compliance staff out in the field.
3. Rules compliance staff conduct tests in the field and input the results of these tests into MTA's custom safety management system (SMS) software.

An accountability structure is built in to the program; the tiered structure ensures appropriate delegation of authority commensurate with managers' daily roles. Additionally, this structure supports effective, efficient communication throughout the program at all levels of leadership.

Uniform Program Mechanics Ensure Consistency Across Participating Departments' Data

The participating departments assign management staff who have undergone classroom and field training on the SRCP to conduct unannounced observations in the field as rules compliance staff. During these hour-long observations, these staff determine whether or not observed operators comply with a specific safety-sensitive rule (e.g., speed restriction) for which they are testing. The observers record the tests results on a test-type specific observation form and immediately verbally reinstruct all noncompliant operators. Following field observations, rules compliance staff input the observation data into the software (discussed in detail below), which automatically sends the entry to the testing coordinator for a quality control check and approval.

Shared Departmental Responsibility for Conducting Field Tests Buffers Manpower Constraints

Multidepartmental participation ensures that field observations are continually conducted each month, despite manpower fluctuations. Five departments conduct field tests; while metro, light rail, and bus test solely within their own mode, the safety department and operations training department perform tests across all three modes. Consequently, staff from three different departments observe operators from each mode. This structure ensures a consistent stream of observation data as well as interdepartmental collaboration to resolve safety issues that arise. Further, this shared responsibility ensures a consistent level of supervisory presence in the field, demonstrating the agency's commitment to safety and serving as a constant reminder to staff that safety is everyone's responsibility.

Figure 1 illustrates this interdepartmental collaboration that characterizes the program. Together, these departments collect a pool of observation data from the field, to which the committee responds at monthly meetings. Collectively, departmental leadership identifies emerging safety trends from field data in the field, issues responsive corrective actions to address these trends, and tracks progress over time as to the effectiveness of targeted corrective actions.

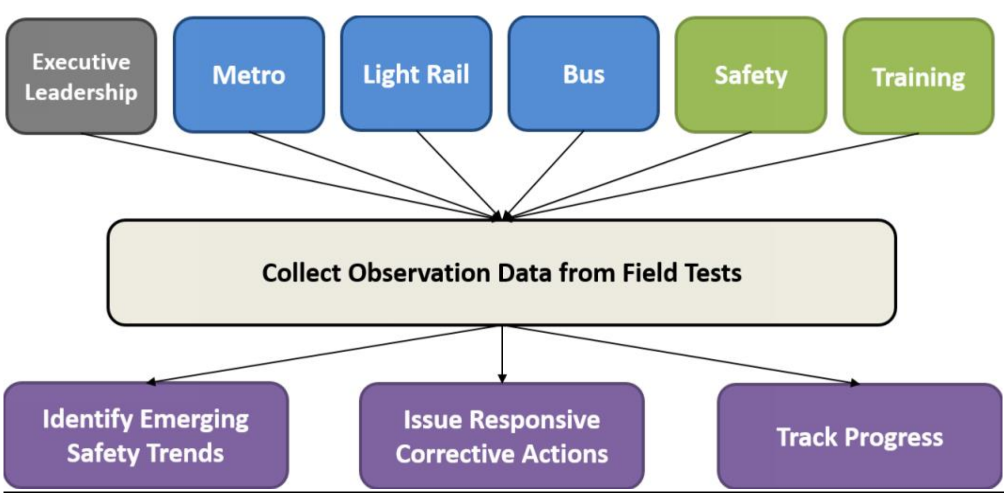


FIGURE 1 Shared departmental responsibility.

A Growing Library of Tests Allows the SRCP to Evolve with Agency and Industry Trends

The program is designed with built-in flexibility. Each mode commenced its testing program with three initial types of compliance tests (e.g., the Radar Test assesses operators' compliance with speed restrictions), based upon previous areas of concern. By limiting the number of tests in early phases of program development, the MTA was able to focus on program mechanics, thus ensuring that program execution became part of the fabric of supervisory staff's daily responsibilities.

The MTA has since expanded its library of tests beyond this "starter library" to capture a broader view of rules compliance across operations. The committee easily adds these new tests, targeting additional safety rules based on concern within the agency as well as the industry at large. Table 1 itemizes these additional tests, some of which are in early development stages, others of which have already been implemented. Over time, a library of test types built upon trends and concerns from within the MTA as well as across the transit industry will further reinforce the SRCP's ability to target safety across all operations and, ultimately, create a safer system.

A Targeted Monthly Observation Schedule Ensures Comprehensive System Sampling

The SRCP is designed to optimally allocate staff's time to complete a minimum representative sample of operations. The committee creates a monthly observation schedule that outlines required observations for each department, determining the test type, location, and testing period (peak, off-peak, or weekend). This schedule ensures that rules compliance staff's efforts are distributed across the geographic service area and throughout all hours of operation, targeting problem areas as appropriate. For example, bus operations faced consistent compliance issues at rail crossings at specific locations. Over the following 2 months, the observation schedule targeted these same locations as well as select alternative locations to determine the extent to which low compliance was due to location characteristics or operator fault.

Codified Linkage to Existing Discipline Policies and Training Programs Ensures Uniform Corrective Actions

The MTA is currently revising its progressive discipline policy, referred to as the Safety Performance Evaluation System (SPES), in each of its core modes. This policy assesses cumulative points against employee records for safety rule violations and requires that

TABLE 1 MTA's Growing Library of Test Types

	Metro	Light Rail	Bus
Starter tests	Door Radar Hand signal	Bar signal Radar Hand signal	Intersection Radar Rail crossing
Additional tests since inception (under way or under development)	Right-of-way Dark signal Radio communications	Right-of-way Station stop Yard movement Radio communications	Service stop Yard or garage movement Seatbelt Radio communications

employees received appropriate reinstruction or retraining. Accordingly, all of the SRCP tests align with violations codified by the SPES. While the SRCP provides for unannounced compliance testing (i.e., evaluation) for specific rules, the SPES prescribes uniform and progressive responses to rules violations. Together, MTA's rules, SRCP, SPES, and training are designed to align, enabling efficient and uniform responses to union employees cited for violating safety-sensitive rules.

Custom Software Streamlines Implementation and Provides Unprecedented Analytics

The SRCP creates a rich stream of observation data. Each test is designed to collect several data points, such as the date, time, location, employees conducting the test, employees subject to the test, vehicle number, track or route number, compliance determination, and more. With multiple departments conducting field observations, each mode collects thousands of data points each month. The SRCP commenced with data tracking in Excel, but this quickly reached its limitations; with limited staff time, it was critical to gather, review, and analyze data in an efficient, highly visual, and user-friendly manner. The MTA's custom SMS software transforms these data from static observation forms into dynamic charts and graphs, which gives management the ability to quickly and easily drill down from historic modal overviews to individual operator results (Figure 2). In addition, the software leverages data validation controls, automates administrative functions and key communications, and ultimately enables senior leadership to make more informed decisions.

Tracking Management Performance

The software tracks the extent to which management staff complete their department's required observations each month. If departments do not consistently complete required observations as set forth in the observation schedule, it is a symptom of management not having a sufficient field presence and also diminishes the statistical significance of the operations data collected. The software displays management performance in the form of automated charts and graphs, which are accessible on-demand by managers and reviewed by executive management at monthly Safety Management Committee meetings.

Bus Operations

ID	Week Beginning	Mode	Department	Test	Testing Period	Location Code	Location Details
692	3/29/2015	Bus	Bus	SRCP-B-001 Radar Test	Peak	All Routes	Back River Neck Rd at Lanflair Rd; Speed Limit is 30 mph
697	3/29/2015	Bus	Bus	SRCP-B-002 Rail Crossing Test	Peak	All Routes	Pratt St at Howard St; at rail crossing
702	3/29/2015	Bus	Bus	SRCP-B-003 Intersection Test	Peak	All Routes	E Biddle St at Caroline St; at intersection
698	4/5/2015	Bus	Bus	SRCP-B-002 Rail Crossing Test	Off-Peak	All Routes	Patterson Ave at Eberle Dr; at rail crossing
693	4/5/2015	Bus	Bus	SRCP-B-001 Radar Test	Off-Peak	All Routes	Eastern Ave at Ashby Ave; Speed Limit is 35 mph
694	4/12/2015	Bus	Bus	SRCP-B-001 Radar Test	Peak	All Routes	N Charles St at W Eager St; Speed Limit is 30 mph
701	4/12/2015	Bus	Bus	SRCP-B-003 Intersection Test	Off-Peak	All Routes	Wright Ave at Harper Way; at unsignalized intersection
695	4/19/2015	Bus	Bus	SRCP-B-001 Radar Test	Weekend	All Routes	The Alameda at Springfield Ave; Speed Limit is 30 mph
699	4/19/2015	Bus	Bus	SRCP-B-002 Rail Crossing Test	Peak	All Routes	Belvedere Ave at Wabash Ave; at rail crossing
700	4/26/2015	Bus	Bus	SRCP-B-002 Rail Crossing Test	Peak	All Routes	Timonium Rd at Greenspring Dr; at rail crossing
696	4/26/2015	Bus	Bus	SRCP-B-001 Radar Test	Peak	All Routes	Eastern Ave at 54th St; Speed Limit is 35 mph
703	4/26/2015	Bus	Bus	SRCP-B-003 Intersection Test	Peak	All Routes	Saratoga St at N Charles St; at intersection

FIGURE 2 Targeted monthly observation schedule from bus.

Tracking Employee Performance at a System Level

The core function of the program is tracking the extent to which operators comply with safety-sensitive rules in the field. By tracking the observation results across operations, the MTA has been able to identify overarching compliance trends. These may be indicative of deficiencies in training, communication, or management oversight. The software analyzes employee performance through dynamic charts, with several layers of drill-down analysis, allowing the Safety Management Committee to evaluate the root cause of failures. These analyses enable management to potentially intervene before these deficiencies contribute to an accident or incident.

Tracking Individual Employees' Performance

In addition to tracking employee performance at the system level, the software also enables analysis at the individual employee level, identifying top performers as well as high-risk employees. Recognition of top performers creates an environment that encourages safe operations; evaluation of these top performers provides a learning opportunity for training staff. Intervention with high-risk employees enables management to potentially reduce the chances of a preventable accident or incident and reinforces a culture of accountability.

Tracking Corrective Actions

In response to compliance rates that dip below prescribed thresholds, departments are required to take corrective actions (e.g., issuing a special bulletin to employees or revising training). Management staff log these corrective actions in the software, where they are visually integrated with the graphs depicting employee compliance trends. This is an invaluable tool; when corrective actions are successful, compliance rates trend upward. Conversely, managers can easily assess if a corrective action does not have the desired impact, prompting them to take a more aggressive approach to curb dangerous employee behavior. Over time, management staff can learn from those interventions that do and do not work, simultaneously creating a library of proven corrective action methodologies they can draw from in the future.

Data Validation Controls

Traditional SRCPs are very "paper-heavy" and depend on the use of programs such as Microsoft Excel for data analysis. These older methods create numerous opportunities for human error. The MTA's custom SMS software leverages input masks and other data validation techniques to minimize typographical and logical human errors. These data validation controls ultimately increase confidence in data quality.

Automated Administrative Functions

The software leverages a sophisticated algorithm to suggest an observation schedule each month based on a small number of user inputs, such as a desire to focus on a particular location or exclude a particular location from the observation schedule. The algorithm helps ensure that over time observations are conducted geographically across the entire service area and across all hours of operation.

The software has also enabled an electronic quality assurance (QA) process. As observations are completed and become available for QA audit, the software automatically displays a queue of forms awaiting approval in a custom homepage for each testing coordinator, providing a convenient link to each specific form for review and electronic signature.

Automated E-Mail Communications

The software generates various key e-mails automatically. Each month, the software directly e-mails the upcoming month's observations schedule, attaching the most recent field observation forms. When rules compliance staff enter completed forms into the software, the software will send an automated notification to the appropriate managers, triggered by any violations observed in the field. This feature enables management to rapidly intervene with the offending employee according to the SPES and training programs. Finally, the software automatically compiles and distributes monthly observation analyses into a printable PDF, which management staff can take to meetings and distribute as appropriate. These automated communications ensure consistent, targeted, and timely communication throughout all levels of management.

PROGRAM BENEFITS, RESULTS, AND RETURN ON INVESTMENT

Over the first 20 months of implementation, the MTA's SRCP has highlighted a number of previously undiscovered problems; some of these were evident immediately, and others were revealed over time. MTA used the trends and findings revealed through SRCP testing data and dynamic analytics to correct these previously unidentified problems, proactively addressing safety risk across the system before an accident or incident occurred.

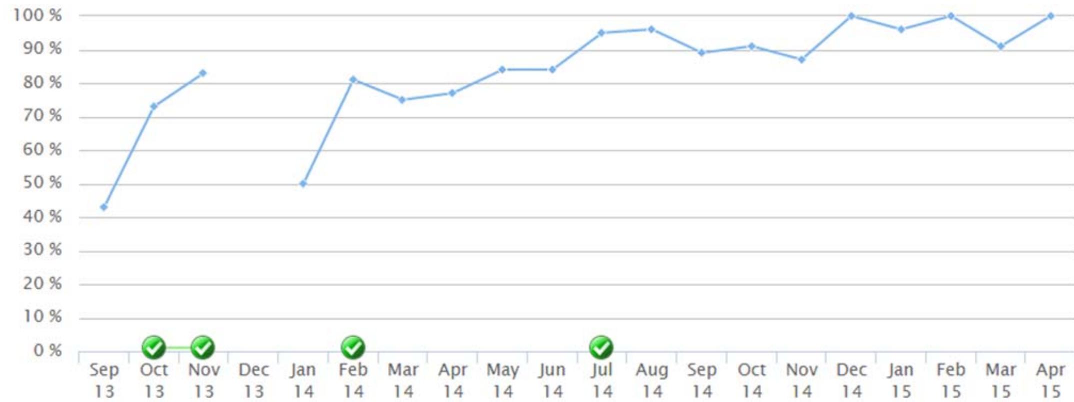
Rules Compliance Rates

Problem: Systemic Rules Compliance Failures

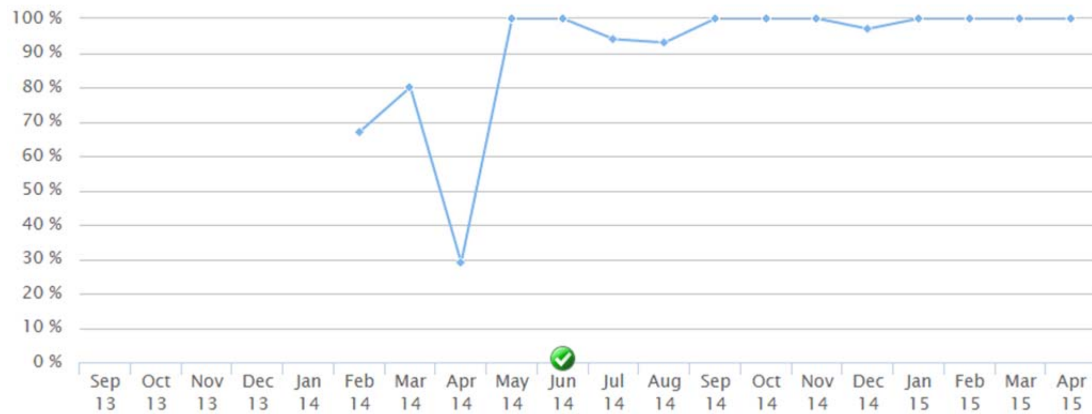
Within the first 5 months of testing in the metro mode, MTA management discovered that 42% of all operators consistently did not comply with a "stop" hand signal. Within the first 3 months of testing in light rail, 44% of all operators tested were also found to be noncompliant with hand signals.

Solution: Targeted Corrective Actions

Both modes addressed these issues head-on, creating special posters and issuing memos to reinforce proper hand signal procedures. As a result of this intervention, both metro and light rail have seen hand signal compliance rates dramatically improve, consistently remaining above 90% for over 8 months (Figure 3).



(a)



(b)

FIGURE 3 Hand signal compliance rates over time: (*a*) metro and (*b*) light rail.

Location-Specific Issues

Problem: Design Issues with Specific Locations

Testing in the bus mode revealed that while operators are generally compliant with at-grade rail crossing rules, they consistently failed at number of locations. Upon investigation by MTA staff, unique design elements of the location were determined to be the cause of these failures, such as multiple rail crossings in close proximity or the presence of signalization.

Solution: Special Operating Procedures

Bus management reviewed all at-grade rail crossing testing locations. Additional analysis determined that the presence of multiple rail crossings, various types of signalization, and other geometric design elements meant that certain locations required additional instructions for observers to fairly conduct testing. Testing locations were subsequently revised, with certain locations removed from testing while others were revised or added. This ensures uniform, consistent, fair testing for all operators that aligns with their rules and training.

Individual Employees Identified as Repeat Offenders

Problem: Operators Identified as High Risk

Across all modes, a small number of employees failed their rules compliance tests more than 33% of the time. While some of these employees have been implicated in past accidents–incidents, others do not yet have an accident on their record; these are now considered high-risk employees.

Solution: Comprehensive Retraining and Follow-Up

Modal management worked with operations training to proactively intervene with targeting retraining, field reinstruction, and follow-up ride checks. As a result of the program, MTA has also been able to address the behavior of high-risk employees as well as recognize those who have been identified as exemplary performers (Figure 4).

Departmental Focus on Safety

Problem: Inconsistent Departmental Performance

While management staff in certain departments were able to consistently perform 100% of their required field observations, other departments consistently performed less than 50% of their required observations; this highlighted an accountability issue with management.

Solution: Executive Intervention

Executive management consistently reinforced the importance of management's role in the SRCP by highlighting the success already achieved in some modes. As a result, departmental

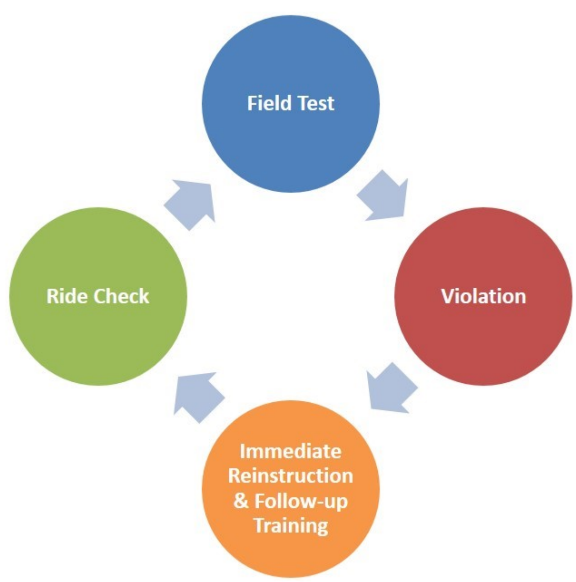


FIGURE 4 Proactive intervention and reinstruction cycle.

performance has dramatically improved along with overall buy-in and support for the program (Figure 5). All three modes have voluntarily increased their number of required monthly observations, with plans to further increase these numbers upon receiving additional field supervisory staff. As a result, the program continues to offer more consistent and increased data sampling on which the committee can base safety-sensitive decisions.

NEXT STEPS IN THE PROGRAM

With the foundation of the program firmly in place and modal testing programs underway for a minimum of a year, MTA has now turned its attention to future iterations of this critical program. Three major areas are at the forefront of MTA's efforts to continue to improve and expand the program.

Expand the Portfolio of Test Types

As previously discussed, each mode commenced its testing program with three test types in its "starter library." This strategic decision to start with a small number of tests was to ease staff into new roles and responsibilities as well as decrease the initial burden on the training staff. Today, the committee continues to expand on these starter libraries, with new tests in design and underway across the three modes. As the program continues to gain significance and buy-in, it will continue to add new tests that are responsive to agency and industry safety concerns.

Link to Other Safety Databases

There are many related databases at the agency. Currently, the committee is working to link accident and training databases with the data gathered through the SRCP. By integrating these disparate data sets through a single web-based portal, MTA's SMS software will enable management to perform cross-analysis simply and quickly on demand. As a result, the agency will be able to ask safety-critical questions that can only be answered through comprehensive data integration.

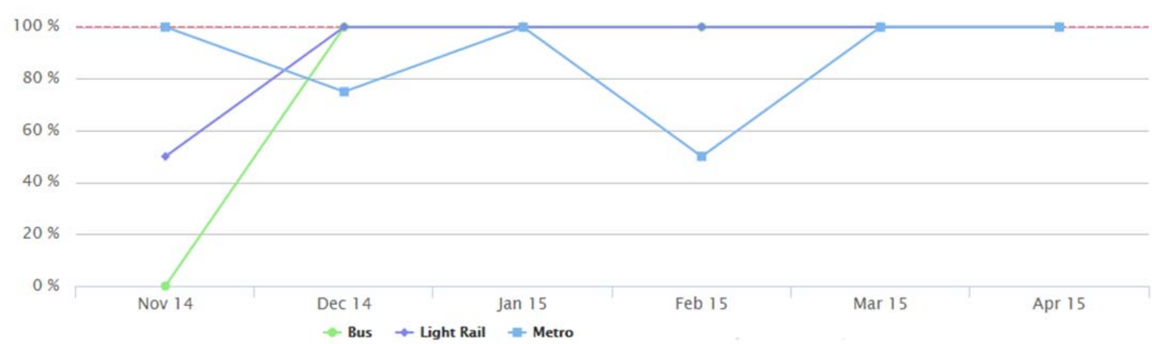


FIGURE 5 Improving departmental participation in recent months.

Create Agencywide Safety Dashboards

Recently, the committee decided to increase the transparency and application of the program's data by creating dynamic agencywide safety dashboards (Figure 6). These mode-specific safety dashboards are designed to present high-level data that can be accessed not only on-demand through the MTA's intranet, but also displayed in dispatch areas and employee break rooms. The availability of this timely information will both foster a sense of program transparency as well as increase awareness of safety issues and concern for those whose behavior matters most: the operators and controllers.

CONCLUSION

The MTA's SRCP builds on industry best practice. It is compliant with APTA RT-OP-S-011-10, aligned with best practices identified through TCRP Report 149, and takes inspiration from peer analysis. The SRCP equips the MTA to proactively correct concerning safety trends identified through unannounced compliance tests in the field. While the program does an exemplary job of tracking trends over time at the agency, modal, and test-type level, it also provides a high level of detail at the individual employee level. This identification of safety risks through the SRCP provides for early intervention opportunities. Conversely, the identification of top-performing individuals allows for a learning opportunity from the industrial psychology perspective, which can better inform improvements to the operations training regimen.

The SRCP's unique program features and customized software enable efficient analysis of safety trends, despite the resource constraints commonly experienced by transit agencies. As a byproduct, the program fosters more informed decision making, improves agency communication about safety issues, and has made a noticeable impact on safety culture.

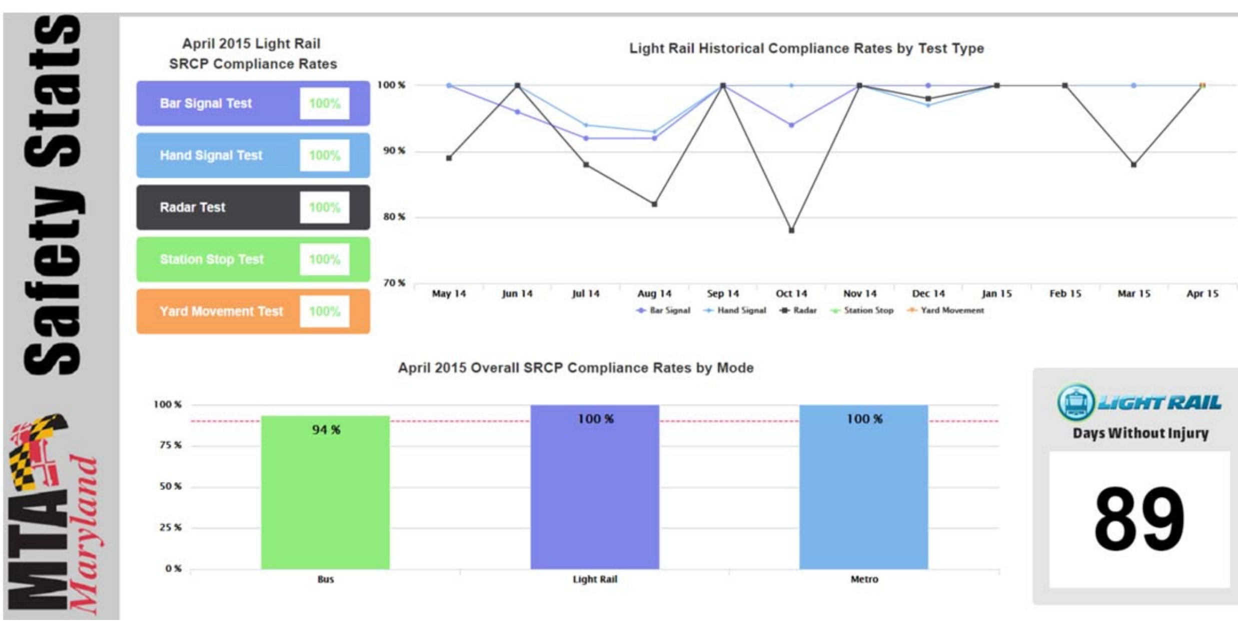


FIGURE 6 Public "Safety Stats" dashboard, light rail.

Taken together, the outcomes from MTA's unique SRCP suggest that every transit property should consider either creating or improving on their SRCP. Agencies should consider using the model MTA has developed and taking the initiative to further improve on it in an effort of continual industry advancement.

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LRT Safety in France

How Are Pedestrians Involved?

MARINE MILLOT
Cerema France

The current literature shows that light rail transit (LRT) systems lead to a complex urban space and create specific accidents, particularly for pedestrians. A better knowledge of these safety problems would enable improvement of the insertion of LRT system in street design. In particular this paper aims to answer: How are pedestrians involved in LRT accidents? Not only by direct accidents but also by indirect accidents when a streetcar doesn't hurt the pedestrian but induces behaviors that lead to accidents. Where are pedestrians involved?

The study is based on the analysis of pedestrian accidents that occurred in streets with streetcars separated from road traffic in four French cities (Bordeaux, Montpellier, Rouen, Strasbourg) for a period of 3 years. The data used are police accidents reports. They enable researchers to collect a lot of information and to understand what happens during the accident and to identify major kinds of problems.

The results show the importance of taking into consideration all the pedestrian accidents. They reiterated the low level of pedestrian perception of the risks involved with streetcars and the importance of making streetcar tracks easier to read. Moreover this highlights the issue of stations. Indeed, while they account for only half of the direct pedestrian accidents, they are the focus of most of the indirect accidents. Securing the crossings when a streetcar arrives remains a crucial question. Finally, in France, young pedestrians aged 11–25 are the most concerned about accidents with streetcars and the leading target for preventive measures.

A streetcar renaissance has been underway in cities around France since the 1980s. Advocated for providing regular, high-performance service, they often require spaces to be segregated. For pedestrians, this leads to a multiplication of the kinds of lanes they have to cross (traffic lanes and streetcar tracks) and traffic directions to be handled (streetcars can run opposite to the general traffic). This increases also the distance of crossing. And pedestrians possess certain unique characteristics and behaviors that must be considered in the planning, design, and operation of pedestrian crossings for public rail transit services: they are slow, flexible, fragile, sensitive to their surroundings; they prefer direct paths; they may be inattentive; and they may ignore warning signs (*1*).

Many international studies agree that streetcars entail specific safety problems for pedestrians (*1–7*). A review of the German literature (*4*) has shed light on the safety problems caused by the succession of differing kinds of lanes, notably when streetcar tracks follow traffic lanes in the pedestrian's crossing direction. Stations are also mentioned as places where accidents between pedestrians and streetcars are concentrated (*8*). Specific analyses of certain layouts such as curbside stops (*9*) have demonstrated that pedestrians run risks when they have to cross street traffic lanes to get on or off a streetcar. These in-depth analyses have also shown the importance of pedestrian accidents with other motorized vehicles, notably cars, in the vicinity of stations (*10*).

These results suggest that streetcars are not only involved in collisions with other users of public spaces, but they can also induce behaviors that lead to accidents. For example, 30% of the children injured near bus or streetcar stops are children who had crossed in front of or behind the bus or streetcar and were hit by another vehicle driving along the street (*3*). Furthermore, not stopping at a red light is more common among pedestrians when they are crossing to get on public transport (*11*). These pedestrians may also lead other pedestrians to cross on the red light with them.

Moreover, pedestrians' perception of their environment is also important in their decisions to cross (*12*), including in the vicinity of streetcar areas (*13*). This could explain certain inappropriate behaviors.

The literature shows the complexity of pedestrian accidentology in relation to streetcars. But existing studies have often been carried out in a targeted manner, by accident location (such as stations) or by type of pedestrian (such as children), and have often been limited to direct accidents between pedestrian and streetcars.

This paper proposes to analyze overall pedestrian accidentology in relation to streetcars, in other words to identify not only direct accidents but also indirect accidents—when the streetcar plays a role in the accident without participating in the collision itself—and to describe all of these accidents according to their location, the kinds of people involved, and the principal accident configurations. The analysis was carried out on four French cities with streetcar networks.

METHOD AND DATA

In France, traffic accidents give rise to police reports. This concerns all accidents occurring on a road open to public traffic and causing at least one victim (i.e., one user requiring medical care and involving at least one vehicle). These accidents may involve all kinds of road users: road vehicles but also pedestrians and cyclists. However, if a pedestrian or a cyclist is injured alone in an accident (e.g., falling on pavement), no police report is generated. Using this report, the police then fill in the national bodily injury accident file (BAAC: Bodily Injury Accident Analysis Bulletin). This file includes detailed data on the features and general circumstances of the accident, the location, the vehicles, and the persons involved. Although they are very useful, these data are limited to statistical processing and do not provide an understanding of accident processes.

The information contained in the accidents reports is more detailed. A complete description of the accident, the protagonists, the vehicles, and the location are given. Then maps are provided representing the accident sequence, along with testimony from the persons involved and from any witnesses, with a summary drawn up by the police. Even though these documents are designed to determine the penal liability of the persons involved, interpreting their content with caution can provide an analysis of accident processes to set an orientation for accident prevention actions.

Seeking a better understanding of the safety problems between pedestrians and streetcars and starting from the principle that streetcars are restricted in their movement by rails, this study was based on the analysis of all the pedestrian accidents occurring on streets with streetcar layouts. The streets studied are those on that run lines A and B of the Bordeaux streetcar network, lines 1 and 2 of the Montpellier network, the single line in Rouen, and lines D and E in Strasbourg. Accidents were analyzed over 3 years, from 2009 to 2011. A total sampling of 190 pedestrian accidents was thus developed.

The streetcars on the streets studied necessarily had a dedicated corridor. In France, shared right-of-way is very rare, accounting for just 2% of the French streetcar network. The stations are all laid out so as to be separate from the sidewalks and dedicated to the streetcar. The features of the lines studied are presented in Table 1.

The sequence leading to each accident was reconstructed using the accident reports. The sequential accident analysis method was used (*14*), breaking the accident down into four main phases. The first corresponds to the driving or travel situation of each of the protagonists before the accident: where were they going, did they know the itinerary, did they use it regularly? The second is the accident situation when the protagonists' interaction began: a pedestrian who starts to cross a street where a vehicle is driving. This situation can lead to an accident if none of the protagonists reacts. The third phase deals with the emergency situation in reaction to which each person adopts (or fails to adopt) measures to avoid the accident: braking, accelerating, modifying their trajectory, etc. Lastly, when the measures prove not to be effective, the impact situation arises: the protagonists collide. Using this accident reconstitution, the role played by the streetcar was determined: (*a*) direct involvement for collisions between pedestrians and streetcars, (*b*) indirect involvement when the streetcar plays a role in the accident without being directly concerned, and (*c*) no involvement by the streetcar; the accident could have occurred on any other street where the streetcar does not run.

Using the accident sequence, certain accident characteristics were identified, such as the location (near a station; type of streetcar layout, lateral, axial, or in a segregated corridor with no street traffic), details of the protagonists (age, severity of the injury, if the pedestrian had or was about to take the streetcar), details of the pedestrian's action (crossing within or outside a pedestrian crosswalk, color of the traffic light if there was one). Accident categories were thus able to be defined for the type of streetcar involvement in the accident.

TABLE 1 Principal Features of the Streetcar Lines Studied

Line	Size of the Urban Area in Question (number of residents)	Length of the Streetcar Lines (km)	Number of Stations (no double counting)
A and B, Bordeaux	740,000	35.8	71
1 and 2, Montpellier	435,000	33.8	55
Rouen	495,000	15.2	31, including 5 underground with no interface with pedestrians
D and E, Strasbourg	475,000	18.8	37

RESULTS

Between 2009 and 2011, 190 pedestrian accidents occurred on the streets studied. For 12 of these pedestrian accidents it was not possible to determine whether the streetcar was involved in the accident. As a minimum it can be said that the streetcar was not directly involved because it was not mentioned in the protagonists. But the report did not provide enough information to determine whether it had an indirect impact.

Of the remaining 178 pedestrian accidents (Table 2), 58 had direct streetcar involvement and 47 had indirect involvement. The share of indirect accidents (26%) is a bit weaker than the share of direct accidents (33%), but it is far from being insignificant.

Concerning the cities where the streetcar lines were studied, 1,419 accidents with pedestrians occurred from 2009 to 2011. So the pedestrian accidents linked to streetcar directly and indirectly represent 7.4% of the all pedestrian accidents.

In the national BAAC file for 2011, pedestrians between 11 and 25 years of age accounted for 34% of direct pedestrian accidents with streetcars. But this age group is more strongly represented when the totality of pedestrian accidents with a streetcar influence and in particular indirect accidents is considered. In the four cities studied, this category of pedestrians is concerned by 58 cases among the 105 pedestrian accidents with direct or indirect streetcar involvement (55%). These results differ in other European countries, where people over the age of 60 are more often involved in accidents with streetcars (*4*). In Zurich, for example, their involvement reaches 66% of direct pedestrian accidents with streetcars.

Description of Direct Accidents with Streetcars

Among the 58 direct pedestrian accidents with streetcars, 29 occurred in stations and 29 outside stations. Given the specific effect of stations on pedestrian accidentology (*8*, *9*), the descriptions of the principal accident categories were divided up depending on whether or not there was a station.

Description of Direct Accidents with Streetcars in Stations

In stations, the majority of pedestrians involved in accidents were streetcar passengers; they had just gotten off or were about to get on (19 cases versus eight nonpassengers and two undetermined cases).

TABLE 2 Type of Streetcar Involvement in Pedestrian Accidents Occurring in Streets with Streetcar Layouts from 2009 to 2011 in Four French Cities

Streetcar Involvement in Pedestrian Accidents	Number of Cases
(A) Direct involvement	58
(B) Indirect involvement	47
(C) No streetcar involvement in the pedestrian accident	73
(D) Undetermined (not enough information)	12
Total	190

In nine cases, the pedestrian accidents involved falls on the platform with people ending up within the streetcar clearance and being hit by a streetcar coming into the station. In a few cases, alcohol caused the pedestrian to lose balance. In others, the pedestrians were elderly and had difficulties walking. Lastly, in two cases, weather conditions played a role: rain and snow making the platform slippery.

Another category (eight cases) concerns pedestrians who were on the platform and had just gotten off the streetcar or were waiting to get on and who crossed the rails directly at the platform to go to the other side of the street or the other side of the station. The conductor pulling into the station was taken by surprise. They did not take the pedestrian crosswalks next to the station. Three additional cases concerned pedestrians with the same accident description combined with masked visibility created by a streetcar stopped in the station.

A last category (five cases) involved pedestrians who crossed the street to reach the station, first crossing traffic lanes and getting hit on the first rails they crossed, no matter whether they were positioned laterally or axially. These pedestrians were often in a hurry and either had seen the streetcar coming and thought they had time to cross in front of it or had not checked traffic in the right direction. In one case the pedestrian had crossed on a red light, in the other cases they had crossed outside the pedestrian crosswalks.

Description of Direct Accidents with Streetcars Outside Stations

Outside stations the majority of pedestrians involved in accidents were not streetcar passengers (22 cases versus three passengers and four undetermined cases).

A first category of accidents (11 cases) concerned a pedestrian walking along the streetcar and who suddenly crossed outside a pedestrian crosswalk when a streetcar was coming from behind. Or the tracks were positioned laterally (nine cases) and the pedestrian was walking on the sidewalk. In most cases, the pedestrians were distracted (earphones, mobile telephone, dog on a leash, etc). Or the tracks were positioned axially (three cases) and the pedestrian was walking along the tracks. The surfacing of the tracks is done with grass, which did not discourage pedestrians from walking there.

Lastly, a second category (seven cases) involved crossing on a pedestrian crosswalk. The pedestrian crossed traffic lanes before coming to the tracks and continued crossing even though a streetcar was pulling in. In half of the cases, the pedestrians crossed on a red light, in the other half there was no traffic light. Poor weather conditions or reduced visibility can explain part of this phenomenon. For a few cases, the pedestrians were disabled and had reduced analysis capacities. Lastly, some were affected by a distractor (earphones or mobile telephone). The tracks were situated in a lateral or axial position.

Table 3 summarizes the principal categories identified for direct accidents with streetcars. Most are in keeping with the literature (*15*), according to which pedestrians have a low level of risk perception for streetcars. This is confirmed outside stations, where pedestrians, who are rarely streetcar passengers, are not very aware of its presence and are hit while suddenly crossing the tracks along which they were walking. But this is also observed in stations when pedestrians, even though they are streetcar passengers, are hit when suddenly crossing between the rails.

TABLE 3 Principal Accidents Categories for Those Directly Involving Streetcars (A)

		Number of Cases
The pedestrian falls on the platform and is hit by a streetcar pulling into the station		9
The pedestrian on the platform crosses the tracks directly, outside the pedestrian crosswalks	Without visibility being masked	8
	Visibility masked by a streetcar stopped in the station	3
The pedestrian crosses the traffic lanes and is hit on the first rails crossed. Crosses suddenly to reach the station		5
The pedestrian walks along the streetcar outside the station and suddenly crosses when a streetcar is coming from behind		11
The pedestrian crosses the traffic lanes outside the station and is hit on the first rails crossed		7
Other cases		14
Total		58

Description of Indirect Accidents with Streetcars

Among the 47 indirect pedestrian accidents with streetcars, 41 occurred in stations and six outside stations. Accident categories can be defined for each of the cases that occurred in station.

In general, the pedestrians involved in the accidents were mainly streetcar passengers (42 cases versus three nonpassengers and two undetermined cases).

A first category of accidents (15 cases) concerns pedestrians who ran to get to the streetcar station and were hit by vehicles driving on the street. In 11 cases, the pedestrians crossed outside the pedestrian crosswalks. In four cases, they crossed the street on a pedestrian crosswalk when the light was red.

In addition to this category, nine cases concerned pedestrians who suddenly crossed to reach the station with visibility masked by stopped vehicles (in six cases it was a bus from which the pedestrian had just got off) and were hit by vehicles driving on the street. In six cases, the pedestrians crossed outside pedestrian crosswalks. In three cases, they used a pedestrian crosswalk without a traffic light.

Table 4 summarizes the principal categories identified for indirect accidents with streetcars. These mainly concern pedestrians crossing at stations (41 cases). Among these, 21 crossings were outside pedestrian crosswalks, 10 on pedestrian crosswalks with a red light, seven on pedestrian crosswalks without lights, and three on pedestrian crosswalks with a green light (the vehicle ran the red light). When pedestrian crosswalks are equipped with traffic lights, more accidents happen when crossing on a red light. This is in keeping with the literature (*11*).

TABLE 4 Principal Accidents Categories for Those Indirectly Involving Streetcars (B)

		Number of Cases
The pedestrian suddenly crosses to reach the station and is hit on the street	Without visibility being masked	15
	Visibility masked by a vehicle stopped in general traffic	9
The pedestrian gets off the streetcar, crosses the street suddenly, and is hit on the street		17
Other cases		6
Total		47

DISCUSSION AND CONCLUSION

Pedestrian accidents are a major issue in tram safety. In 2011, in French cities equipped with streetcars, 148 accidents with streetcars occurred in which 60 directly involved pedestrians (40.5%).

The results presented show the importance of taking into consideration all the pedestrian accidents in relation to streetcars, no matter whether they are directly or indirectly involved. For the sampling of 190 accidents studied, 105 were linked to a streetcar, 55% of them directly and 45% indirectly. A better understanding of indirect accidents provides a more comprehensive view of safety problems for pedestrians.

This sheds light on those points where accidents are concentrated, such as stations. Indeed, while they account for only half of the direct pedestrian accidents, they are the focus of most of the indirect accidents. Of the 105 accidents studied in relation to streetcars, 70 occurred in stations (67%).

This makes it possible to better target those persons concerned by this global accidentology. Indeed, if young pedestrians aged 11–25 are highly involved in direct accidents with streetcars, they are even more so in indirect accidents with streetcars, making them the leading target for preventive measures (55% from the totality of pedestrians accidents with streetcars). For example, if communication campaigns are envisaged, they will have to focus on this age group as a priority. So the channels, the nature of the messages used for the campaigns have to be adapted.

Certain limits to this study should, however, be taken into account. Identifying the indirect effect of the streetcar in the accident is based on the wealth of police reports. If the streetcar's role was not indicated as being important by the protagonists, it is not necessarily mentioned in the report. This kind of limit had been analyzed for indirect bus accidents (*16*). The authors concluded that indirect accidents may be underestimated compared with the reality of the situation. In the case of streetcars, however, the layout is consequential enough to leave a mark the protagonists' minds, unlike a simple bus driving along the street. In this study, only for 12 cases out of the 190 studied, it was not possible to determine whether there was an indirect connection. On the other hand, verification was made that these 12 cases did not call into question the indirect accident categories that have been identified, or the conclusions that can be drawn from them.

Detailed accident analyses using police reports provided a better understanding of the sequences. This could be used to orient layout recommendations for pedestrian safety.

In general, the accidents studied reiterated the low level of pedestrian perception of the risks involved with streetcars. Making streetcar tracks easier to read for pedestrians and getting pedestrians to be more vigilant around the tracks remain two major challenges for their safety. The tools proposed by the European COST group on "Operation and Safety of Tramways in Interaction with Public Space" could be usefully implemented in response to these two goals (*17*).

Concerning stations, where large shares of accidents are concentrated, layout recommendations should situate stations in their overall environment and look as closely at the interplatform area as at the access routes from the sidewalks. Securing the crossings when a streetcar arrives remains a crucial question. The phenomenon of hurried pedestrians, notably young people, running to catch the arriving streetcar has once again been demonstrated in this study. The majority of pedestrians are hit when crossing outside a pedestrian crosswalk or when crossing on a red light. Guidance toward pedestrian crosswalks could be reinforced by incentive systems (comfortable paths with appropriate markings) or coercive systems (barriers). Adjustments to traffic lights could also be studied to make pedestrian crossings safer, especially since various studies have shown that pedestrians comply with traffic signs and stoplights better when they are adapted to their needs (*11*, *18*).

These results are partly linked to the French characteristics, where particularly streetcars are separated from traffic, priority is given to streetcars in junctions thanks to traffic lights. But they show the importance of in-depth analysis of safety. This one highlights the main hazards concerning a kind of third party. It can orientate recommendations in layout. It can also guide safety campaigns: to better know the target, to adapt channels to touch them.

These conclusions could be reinforced by an overall safety analysis of other sites. The safety assessment of measures already implemented in certain countries could also be interesting for confirming layout recommendations.

ACKNOWLEDGMENTS

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Lessons Learned
The Price of Compromise

Safety Management in European LRT Systems

Some Tools for Collecting and Using Accident Data

DOMINIQUE BERTRAND
CEREMA, France

LAETITIA FONTAINE
Service Technique des Remontées Mécaniques et des Transports Guidés, France

The TU1103 Action funded by European Cooperation in Science and Technology (COST) aimed at contributing to improve tramway safety through the management of data collection and the design of tram insertion into urban space. It has shown that across all the countries involved exists a great diversity of light rail transit (LRT) systems and safety management mechanisms. Despite this diversity, a consensus was reached about some conclusions regarding the nature of safety issues, the need for relevant information, and the operator's essential role. This has enabled researchers to lay out some practical recommendations. The advantages and constraints of national databases have been listed, and some other sources of relevant information have been identified to complement them.

In any kind of organization and at any level of importance given to safety, the existence and quality of data remains a crucial pillar, and the operator is the core actor in the collection and use of information. Regarding data collection, an ideal accident report was elaborated, both to propose the relevant data considered necessary to get a good understanding of accidents and to aim at a sufficient quality of information, while considering the practical conditions of data collection in a realistic way.

Regarding indicators, it is essential to set up clear definitions and methods of calculation, and moreover to use figures in a context-related way. The aim is not to compare one line or network with another but to identify trends in order to assess measures and policies; an interesting output of data use is identification of hotspots on networks.

INTRODUCTION

This project, undertaken from 2011 to 2015 with support from COST, aimed at bringing together various stakeholders dealing with LRT issues across Europe, in order to share experiences and identify key recommendations about safety improvement. This process was rather new at this scale, and any reference to such wide networking experience was not found.

This paper presents some of the results of this project, focusing on two specific ways to improve safety: ensuring better information sharing and knowledge management through improved accident reports, and identifying network hotspots: accident-prone locations on the network.

After a brief overview of the Action's scope and general results, this paper proposes an ideal accident report and suggests concrete indicators to improve data collection and information sharing. Then, the concept of "network hotspots" is introduced, and how it can contribute to improve safety management for tramways is demonstrated.

THE TU1103 COST ACTION "OPERATION AND SAFETY OF TRAMWAYS IN INTERACTION WITH PUBLIC SPACE"

Aim, Actors, and Organization

The Action did not look at accidents between several rail vehicles, or at infrastructure or rolling stocks disorders: the work was focused on interaction between streetcars and other users of the public space, which actually is the main safety issue for tramways systems running there.

COST Actions are not pure research or study initiatives, but rather networking activities leading partners to share ideas and experiences in a bottom-up process (*1*).

The Action involved 35 organizations from 15 countries [including the International Association of Public Transport (UITP)] from 2011 to 2015. They were various entities, such as regulation offices, public transport authorities, operators, and research institutions and study bodies from both Western and Eastern Europe.

The project was implemented in 3 phases as Figure 1 shows. Throughout the Action, over 10 meetings were conducted, involving plenary sessions, technical visits, and working groups. This process was concluded by a final conference organized in September 2015 and the publication of a series of deliverables (*2*, *3*).

General Results Regarding Streetcar Networks and Safety Management

The situation varies a lot from one country to another, both in terms of LRT and streetcars system development but also regarding organizations and safety monitoring procedures (*4*).

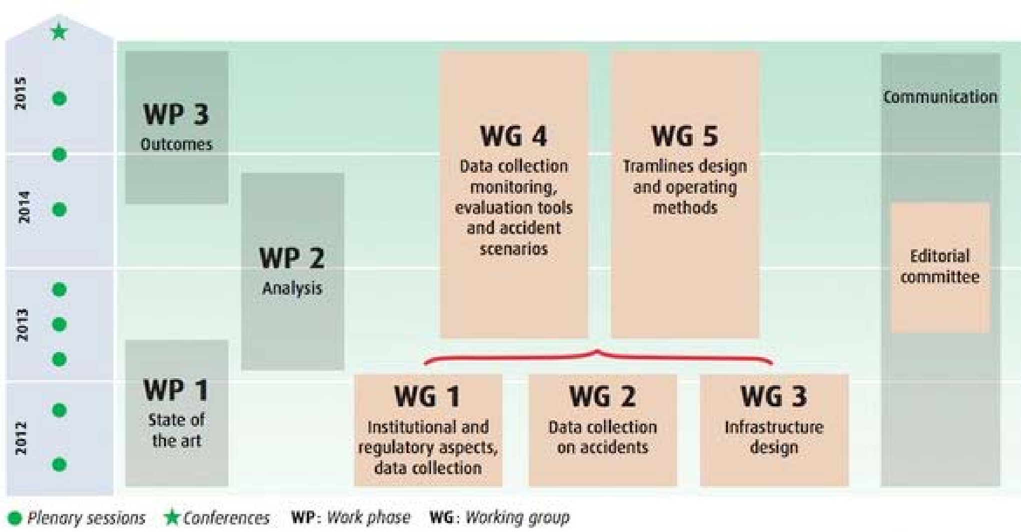

FIGURE 1 TU1103 Organization and schedule.

Contexts vary greatly in terms of number of networks, length of lines, regulation, and actors of public transport systems. In some countries, streetcars have been widespread for more than a hundred years, while in others it has only recently been introduced again or for the first time. Big differences also exist around rolling stocks, layouts, and ways of operating.

On the issue of safety, different methods and ways of considering it have also been observed, ranging from well-defined and shared approaches at the national level to individual processes led by operators. However, some common recommendations have emerged from these exchanges:

- The core level at which to deal with safety is the network.
- An essential actor is the operator, especially for data collection.
- Relevance and quality of information are fundamental issues in the process of data collection.
- Safeguards need to be taken and objective limits of data to be shown.

ACCIDENT DATABASES

From reporting an accident in the field to compiling statistics and analysing them, data collection and usage involves a whole process. Obviously, accident data should first be recorded and used locally; this is often done by the tram operator or the municipality. But these data can also be used on a larger scale: Accidents may also be evaluated on a broader basis and in a systematic manner [see UITP Core Brief (*5*)]. However, it will be necessary to define in advance which institution is responsible for managing such databases, for example at the national or European level. In any case, this body or authority should be independent from operators, city authorities, and other stakeholders in order to be able to protect these sensitive data and share only general and anonymous data and statistics.

Setting up a centralized database, for operators and for the state, represents both advantages and difficulties. Only the general ones are presented here.

Advantages of a National Database on Tramway Accidents

A database can be a relevant tool to help people understand how accidents occur, through information about spatial and temporal location, context, circumstances, involved users, consequences, and so on. This requires a precise description of accidents.

Gathering data at a wide scale, as it is done in France at the national level, may contribute to reaching a better understanding of accidents' factors and highlighting of major stakes, as it allows to

- Make a broader analysis based on more than only one network,
- Make valuable statistics (greater sample), and
- Facilitate data standardization and updating.

Through the feedback it enhances, it may improve the safety level: Using more valuable and representative data (due to the number of records) allows improvement of regulations and technical guidelines concerning road and tram safety. Moreover results of data usage bring relevant information for leading projects and modifications on tramlines.

Challenges to Implement a National Database on Tramway Accidents

Working at a nationwide scale necessarily leads to a collective tool, which necessitates inclusive conception processes and sharing guidelines on how to collect and enter data. This leads to

- Have to collect all the data (partial information can reduce drastically any analyses);
- Set up and use a shared nomenclature (e.g., lightly or seriously injured);
- Use a common codification to get homogeneous and comparable data;
- Agree on the way to build, maintain, and use the database, through a rigorous organization and methods of works; the tool must be managed by one entity; and
- Mobilize sufficient task force to manage and update the database on a regular basis.

Databases are usually based on computing tools, which enables stakeholders to work together, share information, answer quickly to specific questions, and conduct cross-analysis (combined use of various parameters). However, great attention has to be paid to the availability and compatibility of tools as multiple versions of a database can prove difficult to combine.

Even at a nationwide scale, a small absolute number of elements can be found regarding one issue, so that data sets cannot be compared easily. It may then be hazardous to do statistical evaluation based on it.

Key Recommendations to Make a Shared Database Successful

In order to achieve effectiveness and efficiency of collecting methods and get high-quality, relevant, and comparable information on events, those methods have to be adapted to the nature of collected information and the diversity of actors:

- Common ways of collecting and reporting accident data must be set up, with forms easy to fill in and clear guidelines; and
- Required means (people, hardware, software) have to be dedicated, and users properly trained.

A correct use of the data will be facilitated if the database is managed by an independent office, which should be responsible for gathering updated data from operators, checking their quality, ensuring confidentiality, performing analysis, and providing assistance to operators.

If the collected data are used well and lead to reliable analysis and effective safety improvement measures, stakeholders will see this as an incentive to feed into the database regularly and accurately. In France the choice has been made to set up a legal obligation for operators to report their data to a state office in charge of this database.

WHAT WOULD BE AN IDEAL ACCIDENT REPORT?

The group has gathered some examples of accident reports to get an overview of practices and an idea of the content and of the key points not to forget. Then in a brainstorming session, an ideal accident report was proposed. Finally, it was checked by all operators and UITP.

The following ideal accident report is a suggested model adaptable to each operator's needs. But more than a suggestion, it is a detailed list of pertinent data that is strongly advised for tramways operators to collect in order to

- Allow later analysis and better understanding by operators but also researchers, and
- Use data for evaluation and accident prevention.

For many operators the use of template checklists and accident report forms has been successful. Further additional documents include clear sketches of the accident scene, testimonies of the driving personnel and witnesses, black box recordings, pictures (survey of accident scenario, damage of vehicle and other details), and, if possible, video recordings. A homogeneous design of these documents within the operating company can ensure consistent data acquisition and evaluation.

If time allows it, someone else other than the tram driver should collect information from this one and other sources about the accident (location, circumstances, etc.), help the driver to deal with passengers, and save time to restart the operation. This person different from the operator should reach the accident place as soon as possible and collect the following data:

- Identification and location
  - Line number, stop, junction, time and date, vehicle number, and
  - Precise address, house number, GPS coordinates, satellite map, network map, overhead pole.
- Type of location (Figure 2)
  - Multiple choice: Junction (roundabout, left turn, with/without traffic lights), pedestrian crossing, station, running section, and
  - Type of alignment (pedestrian area, completely segregated track, mixed traffic, lane shared with bus) and type of segregation (physical or visual).
- Environment
  - Fog, snow/ice, rain/storm, leaves on tracks, and
  - Operational disturbances: degraded service, works, temporary speed limits, maintenance, and manifestations.
- Actors
  - Identification of tram vehicle, characteristics of third party (e.g., age, sex);
  - Tram driver's name;
  - Involved persons or vehicles (passengers, third parties); and
  - Witnesses (if possible).
- Description of accident
  - Drawing or sketch [of intersection, vehicle and persons movements, place of impact on vehicles, signal type (dynamic/static), and location], pictures (Figure 3);

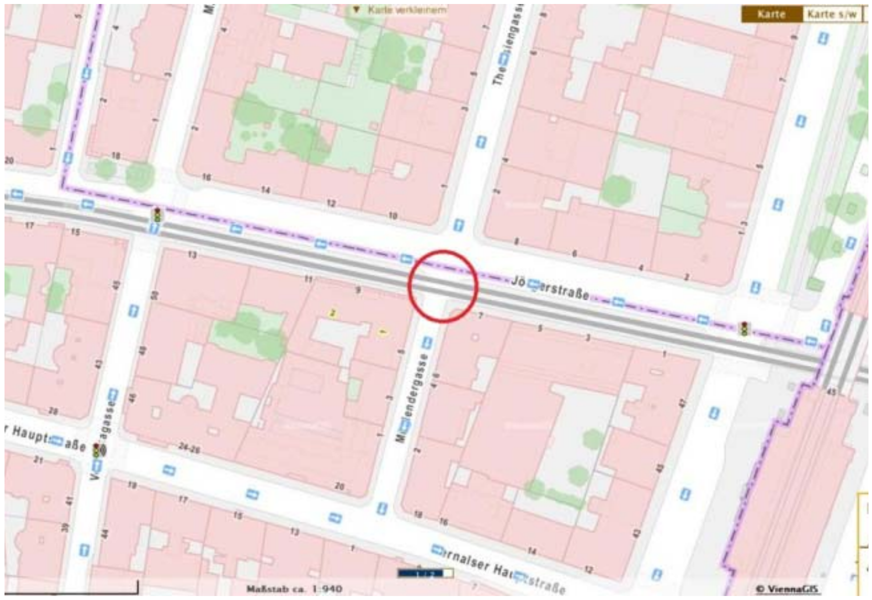

FIGURE 2 Ideal accident report: location of accidents.

– Direction of travel (track 1 or 2 for tram), road (for other involved party);
– Mark on the floor with precision the final position of the involved part of the tram;
– Interview with tram driver;
– Interview with car driver and witnesses (if possible);
– Classification of accident: use local form (if available);
– Causes: left turn, distraction, red light crossing, unauthorized maneuver, lack of visibility (influenced by geometry, obstacles, traffic, weather, lighting conditions) etc.;
– Description of any unusual facts (consider collecting information for human factor postanalysis); and
– If risk management in place, assign risk to incident.

- Technical data
  – Black box: Speed, emergency brakes, bell, turning signal;
  – Radio exchanges recordings;
  – Closed-circuit television (CCTV);
  – Switches and trackside signaling systems; and
  – Traffic lights state (phases).
- Consequences
  – Personal [severity of the injuries (light, medium, severe, deceased)] for staff, passengers, and third parties;
  – Material (to tram, to third-party vehicle, or element): severity of the damages (light, medium, severe), technical report if available; and
  – Infrastructure [severity of the damages (light, medium, severe)];
  – Operational (cancelled trips, delays, overspills);
  – (Suggested) classification for consequences:

FIGURE 3 Ideal accident report: sketch over photo.

1. Accidents with injuries or heavy material damage,
2. ("Regular") accidents, no injuries, and
3. Events with no further safety-related relevance.

- Entities involved in response
  - Police, fire brigade, ambulance, other resources needed to restore normal operation (internal maintenance, crane), inspector;
  - Trigger of the emergency plan (alert, information to passengers, measures for passengers and third-parties protection, coordination with responsible entities);
  - Expose immediate corrective measures taken by the operator (lower speed) or other implicated organisms (the city);
  - Apparent responsibility: internal, external;
  - Special circumstances: internal fire, suicide, vandalism, terrorism threat, etc.;
  - Possible continuation: decision to establish a further investigation or not; and
  - Author and date of report: inspector's name, date, and signature.

It is necessary to ensure the consistent and professional execution of data acquisition and documentation by the operator. Appropriate commitment by the employees is required to avoid conflicts between data acquisition and other duties on site (e.g., passenger information, organizing replacement services, driver's support). Therefore, in theoretical and practical training, employees acquire the required capacities to take appropriate measures in case of an accident. Employees in charge have to participate in drills and practice their skills in data acquisition to ensure a high quality of permanent and structured internal data.

OTHER SOURCES OF INFORMATION

Collecting data in the field through a standard accident report immediately after the event is the primary way to obtain necessary information about an accident from direct sources.

However, other sources may be used to get relevant information regarding accidents. Moreover, some of them can contribute to improve the quality of analysis while taking into account the context of tramlines and the interactions between streetcars and third parties. Those include for example

- CCTV devices on tracks and in front of streetcars,
- Automated event recorders ("black boxes") on tramways,
- Traffic handling information systems, and
- Police reports.

The last two have already been recognized as useful tools for road safety, so this paper will briefly lay out the relevance of CCTV devices and use of black boxes in emergency brake reporting.

CCTV: Facts Recorded, Use in Campaigns, and Privacy

In certain cases, a very welcome complement to written accident reports can be the moving images that are made shortly before, during, and directly after a collision type of accident. The best positions from where objective and significant videos can be recorded are on the external front of the tram vehicle and outside on the road and/or the railway infrastructure. If they are placed at the best possible spots, they can make a record of the accident that cannot be neglected because it will present facts with exactitude and objectivity: just as they happened, no more and no less. The video enables researchers to observe the dynamic situation, including the collision itself.

Such videos are of a key importance for accident investigators and in some cases they can contribute to assess properly the (correctness of) movements of the individuals involved in the collision and the local circumstances that existed during the unfortunate event.

Another interesting application of CCTV is that it enables communication about accidents, like it is done by many operators, such as LUAS in Dublin. On this Irish network, images from the onboard CCTV system are sometimes used in impressive or even persuasive campaigns (Figure 4). Images are shown of near-misses and conflicts with street users and their dangerous behavior in the traffic scene to discourage such unsafe behaviors on or around its network.

Video images from tram inside cameras are also useful sources. Initially implemented for security, they record the situation of the passengers and/or of the driver and can provide recordings in case of legal claims, for example about injuries inside the tram, due to emergency braking.

An important question in the use of CCTV and other video footage, however, is the issues of privacy. One of the main worries when using these kinds of systems is the respect of data protection laws, which impose some restrictions toward the use of pictures. Generally,

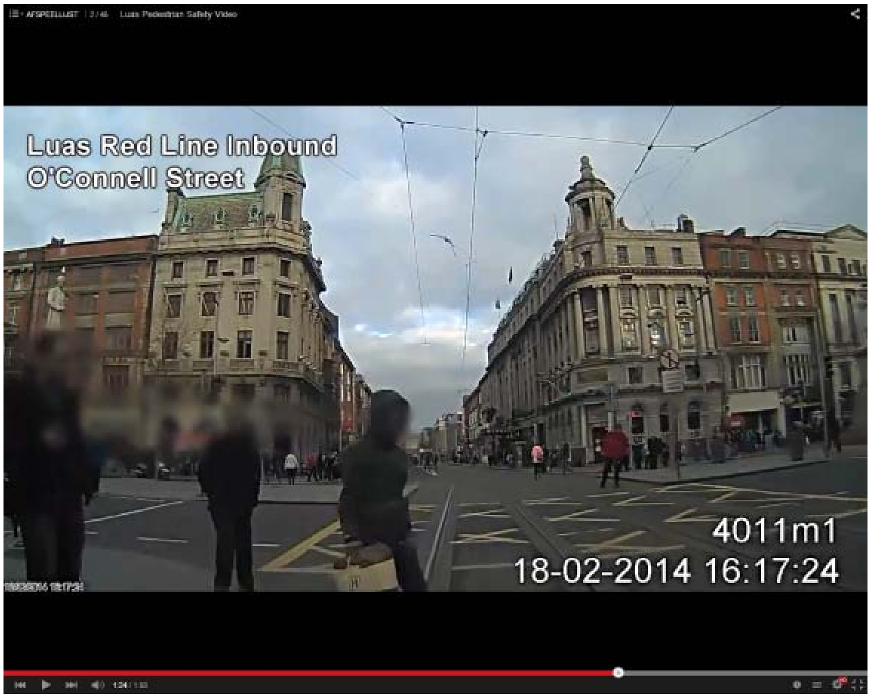

FIGURE 4 Still from film: LUAS campaign.

CCTV images can be used only by some authorized people and may only be recorded if a judge/police asks for it.

Black Boxes' Use: Near-Miss Accidents and Emergency Brake Monitoring

For the full safety management of tram and LRT operations, it is not sufficient to only record, monitor, and analyze incidents and accidents. Near misses can provide critical information as well. Therefore other tools exist or can be applied to get a better insight of the risks in the network on the one hand, and about the driver's behavior on the other hand.

Tram drivers are trained in defensive driving techniques and are constantly looking out for pedestrians, cyclists, and motorized vehicles to prevent a collision. Evidence suggests that these emergency brakes are often in reaction to acts by these third parties. Then, frequency and location of emergency braking are a relevant clue of a precursor to an incident (near miss). Collecting this information will enable operators to gather data on risks and provide useful statistics to prevent accidents by identifying risky places, where no accident has occurred yet but could likely happen in the future.

However, it is important to encourage transparency with tram drivers and prevent the possible negative implications of implementing emergency braking recording. It is difficult to collect these near-missed accidents that need black box identification of location or driver's systematic declaration. And if for example the driver is facing sanctions, he might avoid emergency brakes, therefore compromising safety.

INDICATORS AND OUTPUT OF DATA

Behind the general goal of indicators, there is the characteristic idea of comparing things while using figures. Regarding tram safety, indicators are a useful tool

- To show the trends in terms of safety, to give general information about it through communication and media;
- To identify and rank the stakes by highlighting critical points or situations on existing networks;
- To assess the strategy and efforts implemented to improve safety while looking at impacts of changes in operation or design of lines; and
- To improve the knowledge for planning new lines based on bad or good experiences.

While using indicators, people should rather try to compare data themselves and in time, on another side, making comparisons between networks or parts of it is not often relevant and needs to be very careful because of the different contexts.

Most-Used Indicators

During the state-of-the-art phase, three categories of indicators for tramway safety related to interaction with public space have been identified.

Global Indicators

When following trends to assess safety, a comparison can be made

- In time (i.e., from one year to another), and
- In reference to defined goals (i.e., "0 casualty" policy), which may be compared with figures from other transportation modes or road safety in general.

These are global indicators, gathering those related to

- The whole line or networks (without any reference to the location of accidents),
- The whole period of operation (without any reference to date nor time), and
- The types of events (derailments, collisions, etc.), and severity (casualties, injuries).

All of these indicators are determined without any reference made to causes, period, localization of accidents nor types of users involved.

It was previously stated that urban insertion incidents are the main safety issue for tramways. This is based on an indicator corresponding to the number of events.

Geographical Indicators

When indicators are calculated and used in reference to localization of accidents they may be called geographical indicators. This second group is used to compare figures regarding

- Different parts of networks,
- Various types of places (junctions, stops, etc.), and
- The spatial localization of accidents.

Identification of hotspots (see further) is a good example of this use of indicators (Figures 5 and 6).

Typological Indicators

A third group may be made up of indicators related to the circumstances of accidents and the involved parties:

- Categories of involved persons,
- Periods of time when accidents occur,
- Causes of accidents, and
- Other contextual characteristics.

This paper use figures about severity of accidents to determine that pedestrians and cyclists are the most vulnerable victims during accidents.

Beside these indicators dedicated to safety, other indicators related to accidents' impacts, with an economic or quality aspect, can be identified, such as

- Operation disruption, through its duration or corresponding loss of income,
- Infrastructure and rolling stock repairing costs, and
- Social costs.

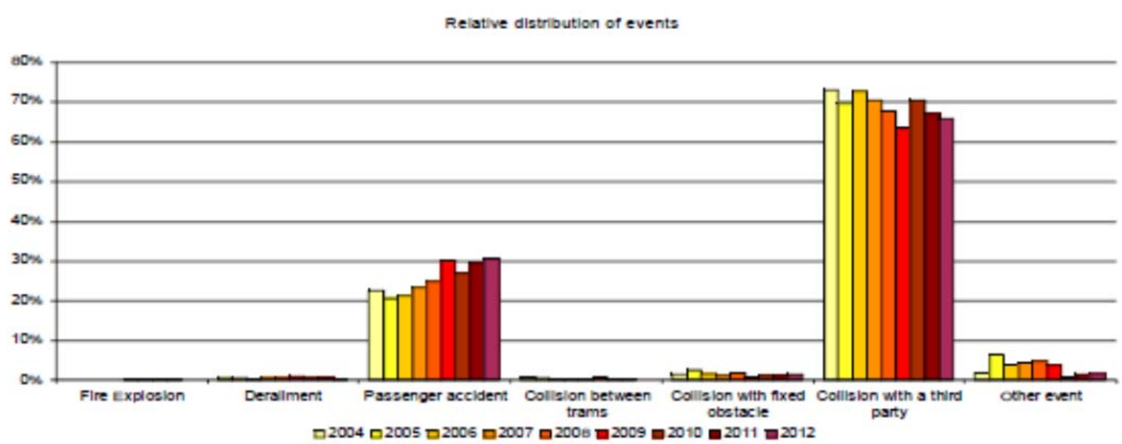

FIGURE 5 Distribution of events on French tramways networks.

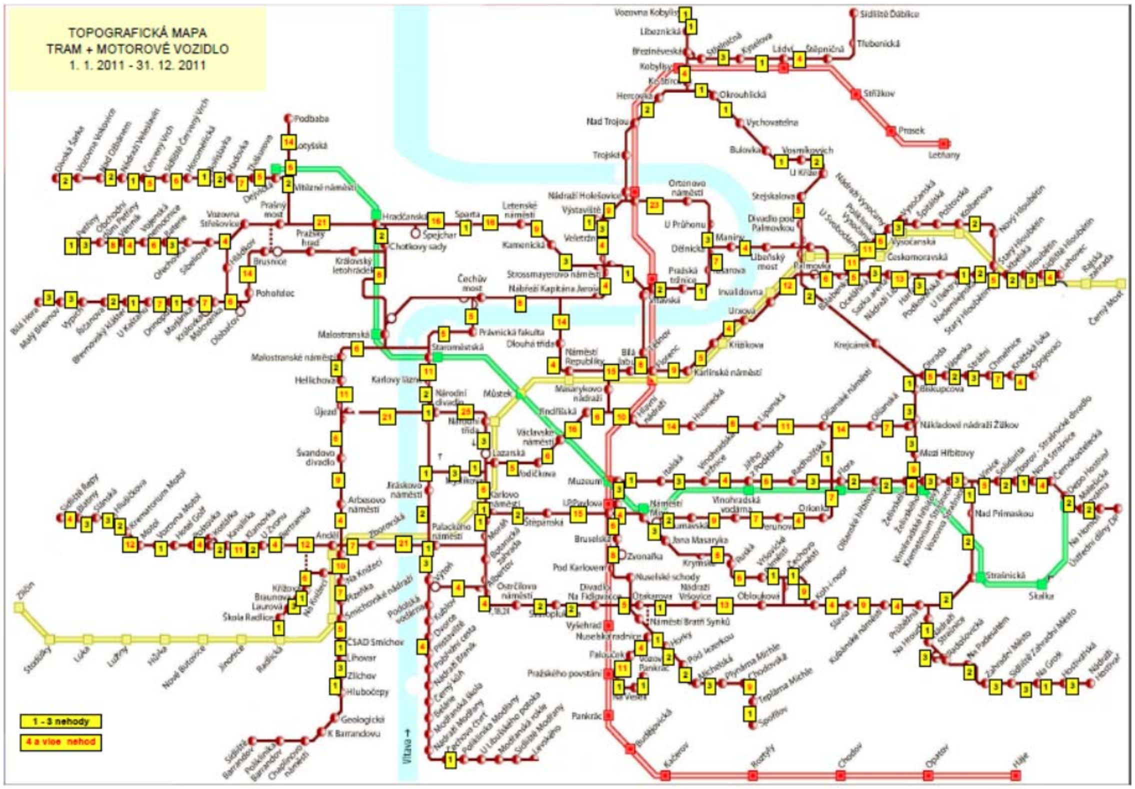

FIGURE 6 Location of accidents on Prague network, Czech Republic.

Limits of Indicators

As far as the aim is not to compare the performance of networks regarding tramway safety, there is no requirement for authorities, operators, or regulation bodies to produce and use exactly the same indicators. This leads to a first limit, which is the availability of data required to produce safety indicators. It must be kept in mind that most accident data are collected by drivers, while they have to deal with the current situation (call for assistance, help the involved person, restart operating, etc.)

A second limit is the existing difference in definitions in the data collection tools. Some countries do not separate collisions between trams and collisions with other vehicles, while fixed obstacles can be part of the rail systems.

Some differences appear about victims:

- Regarding the definition of "injuries": Not all countries use the OECD definition of injured (in Czech Republic, the incapacity to work is used);
- Regarding the definition of "passengers": While a person travelling in the tram is obviously counted up as a passenger, it is not so clear for people staying on platforms at stations, or going out or in the tram: In some countries (i.e., France) they are considered as passengers, but may also be counted up as third parties in others; and
- From what point a person qualifies as a "victim": There are some discrepancies even within countries when a passenger falls down or hits something inside the tram, for example.

A third limit is linked with different context of accidents and operation:

- Frequencies of tramways,
- Nature and level of traffic,
- Layout (segregation of tracks, regulation, and signaling), and
- Users' behaviors.

Moreover, regarding this kind of information, an additional (and strong) limit may be the unavaibility of data regarding car traffic (especially to compare places).

Some Examples of the Most Useful Indicators

Setting up common definitions and similar ways of calculating and using indicators would be a very good thing to enhance mutual comprehension, sharing, and cooperation between these various actors. If figures are not directly comparable, methods, ways of doing, and safety policies are.

To have unique indicators everywhere would also be very useful for researchers dealing with tramway safety and avoid potential misunderstanding in analysis and assessments.

On the other hand, collecting data and exploiting them to produce relevant figures and indicators is a heavy task, requiring human, financial, and technological resources (Figure 7). The choice and definition of these indicators are to be made while considering their relevance and potential use but also by taking into account the fact that data are to be gathered by operators, and originally for most of them by the tram drivers.

Whatever the definitions of data used, the core issue is to make the context of data or indicators explicit and not let them alone without any reference about them, nor definitions used

- In case of several networks concerned (i.e., regional or national database): The same definitions and ways of measures are necessary to make it efficient and coherent; and
- Use of indicators to follow evolution of something requires to maintain same ways of doing over time.

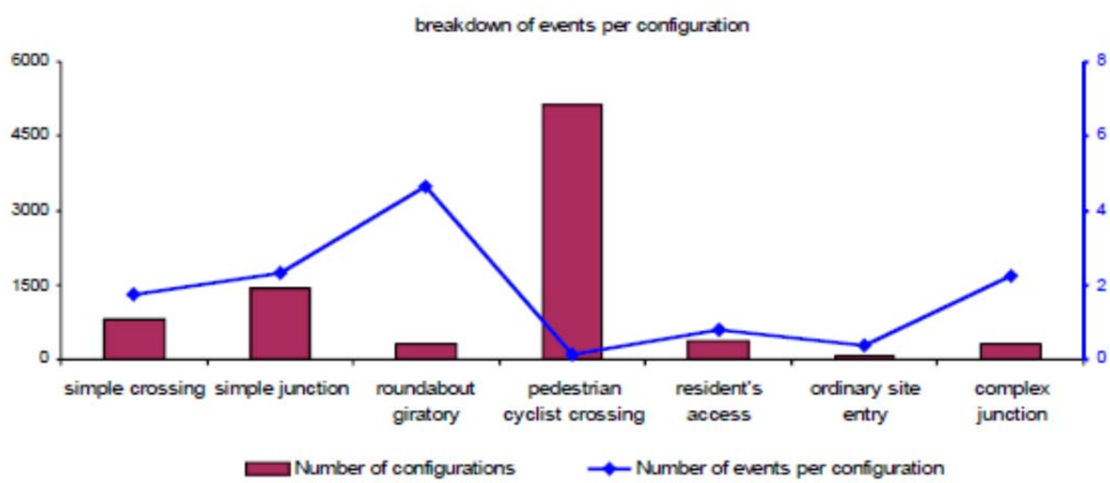

FIGURE 7 Example of graph with number of events for France. Only indicators with a significant number of junctions are relevant (number of configurations = red bars).

Representative indicators must be statistically significant; however, it is difficult to establish a minimum number of records in an absolute way. In any case, an important issue is to give information about the size of the sample (number of events, or configurations, etc.) on which the indicator is based).

Through the discussion facilitated by the project, researchers have identified a list of key indicators that they believe are the most useful for tramways safety monitoring. Among those, they selected a reduced number that can be considered core data to be collected by the operator.

Global Indicators

- Number of accidents: counted accidents during the period (raw data);
- Number of fatalities, injured persons: counted injured/fatalities during the period (raw data); and
- Accidents per train times km per year: number of accidents divided by number of kilometers run (ratio).

Geographic Indicators

- Number of accidents per place: number of accidents per places per period (raw data);
- Distribution of accidents by types of places (relative): accidents for each type of lines section (percentage);
- Distribution of victims by types of places (relative): victims (fatalities, injured) for each type of lines section (percentage); and
- Number of accidents per number of type of places: number of accidents on each type of place divided per number of each type place (during a period, e.g., each year, ratio).

Typological Indicators

- Distribution of accidents by third parties (relative, percentage); and
- Distribution of injured and fatalities by third parties (relative, percentage).

Economic Indicators

- Number of lost kilometers/nb of planned kilometers: total length of non-operated services divided per total length of planned services (ratio).

For each of these indicators, a table has been set up to highlight their main characteristics (Tables 1 and 2).

TABLE 1 Indicator Characteristics: Accidents per Train Times in Kilometers per Year

Nature	Ratio: number of accidents divided by number of kilometers run (better to count all km run on public streets—not only in commercial service) The more a tramway runs, the more interactions it can have with other road users
Category	Global indicator
Representation	Diagram
Spatial field of application	Line(s), network(s) (the most relevant way is to do it line by line)
Period	Any (as far as enough events are concerned to be significant)
Relevant for	Assessment of policy, campaigns, operation methods (evolution in time) Identification of general safety stakes at a large scale (i.e., network, line) Comparison between lines (only if they are similar)
Not relevant for	Comparison between networks, countries with a ranking idea Work on causes, localization, types Looking for detailed stakes

TABLE 2 Indicator Characteristics: Relative Distribution of Accidents by Third Parties

Nature	Percentage; distribution by types of 3rd parties: pedestrians, cyclists, bikers; vehicles Vehicles might be distributed regarding main categories (cars, lorries at least)
Category	Typology
Representation	Tables
Spatial field of application	Network
Period	Any but need enough data
Relevant for	A general overview of involved third parties To highlight the main stakes regarding third parties
Not relevant for	Setting up solutions to avoid accidents at local scale

A MAIN ISSUE AT THE LOCAL LEVEL: THE IDENTIFICATION OF HOTSPOTS

This word “hotspot” means here a specific location on the tram network defined as one of the places in the urban area where the most accidents (collisions) occurred in a fixed period. However, it has appeared during meetings and in questionnaires that this word was used with different meanings and to illustrate different safety approaches.

Indeed, there are several possibilities to identify network hotspots, while counting the number of accidents per location all along the line (for the last year or for the last *x* years) (Figures 8 and 9):

- Then, people may focus on highest ones (in absolute values) or on those that are above a maximum number (e.g., three per location during the period).
- It is also possible to calculate the augmentation/diminution rate and focus on the locations with the highest increase of collisions.

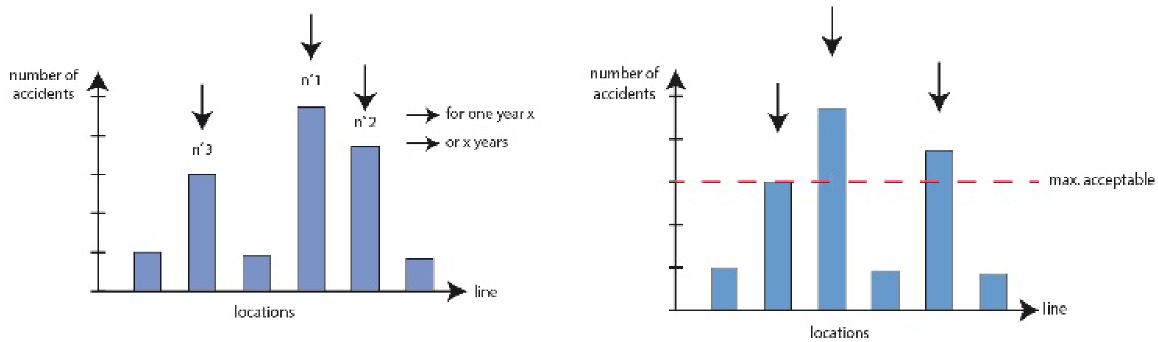

FIGURE 8 Identification of hotspots by number of accidents.

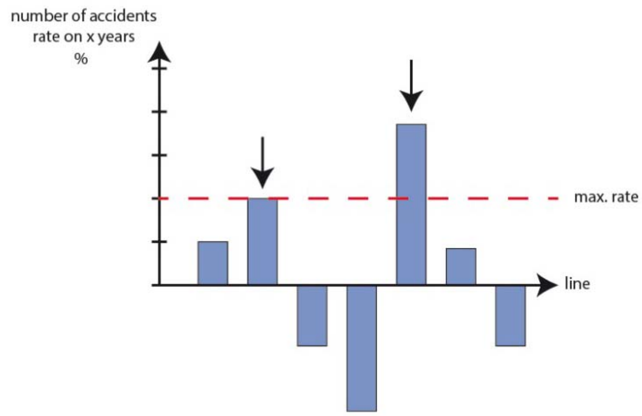

FIGURE 9 Identification of hotspots by trends.

- It is also possible to count the number of accidents per type of causes all along the line (for the last year or for the last *x* years) and to focus on the highest ones (Figure 10).

Besides data regarding accidents (reactive hotspot identification), information given by drivers, line managers, and trainers also contribute to hotspots identification because these people on the field may predict potential accidents somewhere before they happen (proactive identification). One should foresee a channel of communication to that audience and make sure they receive feedback every time they report an issue.

The identification of hotspots is the first step before in-depth post analysis and proposals of improvements (traffic signals, traffic lights, paints, tram driver trainings, safety street usage campaigns). This classification (n°1, n°2, or all spots above *x* accidents on *x* years) is a way to know where to focus efforts (time to observe, to analyze, financial investments).

In conclusion, there are different possibilities to identify hotspots. To count the number of accidents per location all along the line (for the last year or for the last *x* years) and to focus on the highest ones is the most frequent identification.

The consequences of this identification are to know where to put most efforts. There is no management in particular to highlight, but all can be complementary. However, to identify hotspots and have at least a view on a few years on all spots along the tramline is a good starting point.

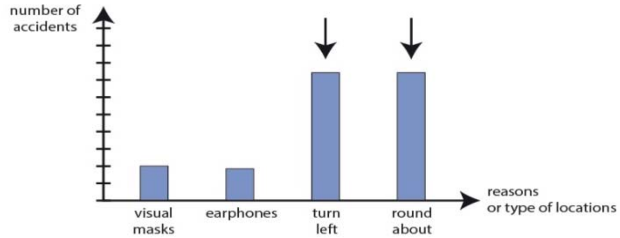

FIGURE 10 Identification of hotspots by causes.

CONCLUSIONS

Whatever the degree of centralization of safety monitoring, data collection on accidents is essential and can be usefully complemented with other sources.

An ideal template of an accident report is proposed, and some relevant indicators are suggested. However, it is neither the researchers' ambition nor mandate to impose a mandatory data collection and usage methodology at the European scale.

This paper then provides an example of how accident data can be used to identify hotspots on a tramway network.

Accident data collection and analysis complement solutions implemented in the field: Hotspots can require layout improvements, and data collection allows for the monitoring of new/improved layout in operation of existing networks as well as during the implementation of new projects.

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Double-Tracking Baltimore's Light Rail Transit System

VERNON HARTSOCK
Maryland Transit Administration

MATTHEW POLLACK
HNTB Corporation

KULDIP BATTU
GL Communications

BALAJI KRISHNAMURTHY
Omni Strategy

The Maryland Transit Administration's (MTA) initial light rail line was planned, designed, and constructed between 1988 and 1993. Implemented without federal funds, the State of Maryland, City of Baltimore, Baltimore County, and Anne Arundel County funded the entire initial project. Unfortunately, funds were not available at that time for a fully double-tracked system along the entire corridor. As a cost control measure, seven sections, totaling 8.2 mi, were designed and constructed as single-track. The existing light rail track configuration was designed to allow trains to proceed at 15-min intervals (headways) in each direction.

In 1997 MTA commenced planning a project to improve headways by providing double track throughout the original light rail system and provide full bidirectional operating capability by upgrading the signal system.

Utilizing a design-bid-build approach, MTA contracted for the full double-tracking of the light rail system and other associated upgrades. Constructed over a period of 4 years, with a final budget of $205 million and an FTA grant of $158 million, the double-tracking program was completed in 2006 and has proven to be a great success for MTA.

As proven by MTA, a rail system can successfully expand from a cost-constrained initial segment to a more-robust system. There are costs associated with delayed implementation and lessons to be learned from the experience of others, lessons that can help other agencies mitigate costs and headaches in the future.

INTRODUCTION

More than ever, transit has an important role to play in connecting other modes of transportation, particularly in urban and suburban areas. In fact, America's most successful and livable cities rely on robust transit systems. Yet such systems, often a combination of light and heavy rail, buses, and other forms of public transportation, operate in a highly competitive, cost-constrained funding environment.

While it appears to be an overwhelming challenge, with proper patience, planning, and recognizing the obstacles facing those seeking to identify sources of funding, it is possible to grow a rail transit system from a limited initial segment to a more robust system. The City of Baltimore's experience provides one such success story others can build on.

IDENTIFYING MASS TRANSIT OPTIONS

The City of Baltimore had been planning rail transit for decades before it became a reality. In 1964, the Baltimore Metropolitan Transit Authority (the predecessor of the MTA) initiated the study of mass transit options for the Baltimore region. The results of this effort were the first definitive plans for a regional, fixed guideway, mass transit system in the area (Figure 1).

Published in July 1968 under the title, "Baltimore Region Rapid Transit System, Feasibility and Preliminary Engineering," the master plan envisioned a 71-mi 6-line system emanating out of Baltimore and heading to toward Randallstown in the northwest, Marley in the south, Timonium in the north, Marlyn Avenue in the southeast, the intersection of Joppa Road and Belair Road (part of U.S. Highway 1) in the northeast, and Chalfonte Drive in the west. Politics and fiscal concerns made for formidable opponents to the hoped-for rail system, and when the heavy rail system (now called Metro) was brought to life as a starter system in 1983, it ran from central Baltimore on a single northwest line to Reisterstown Plaza. The line was extended in 1987 to Owings Mills, which was revised from Randallstown in the 1968 report.

INTRODUCING LIGHT RAIL TO BALTIMORE

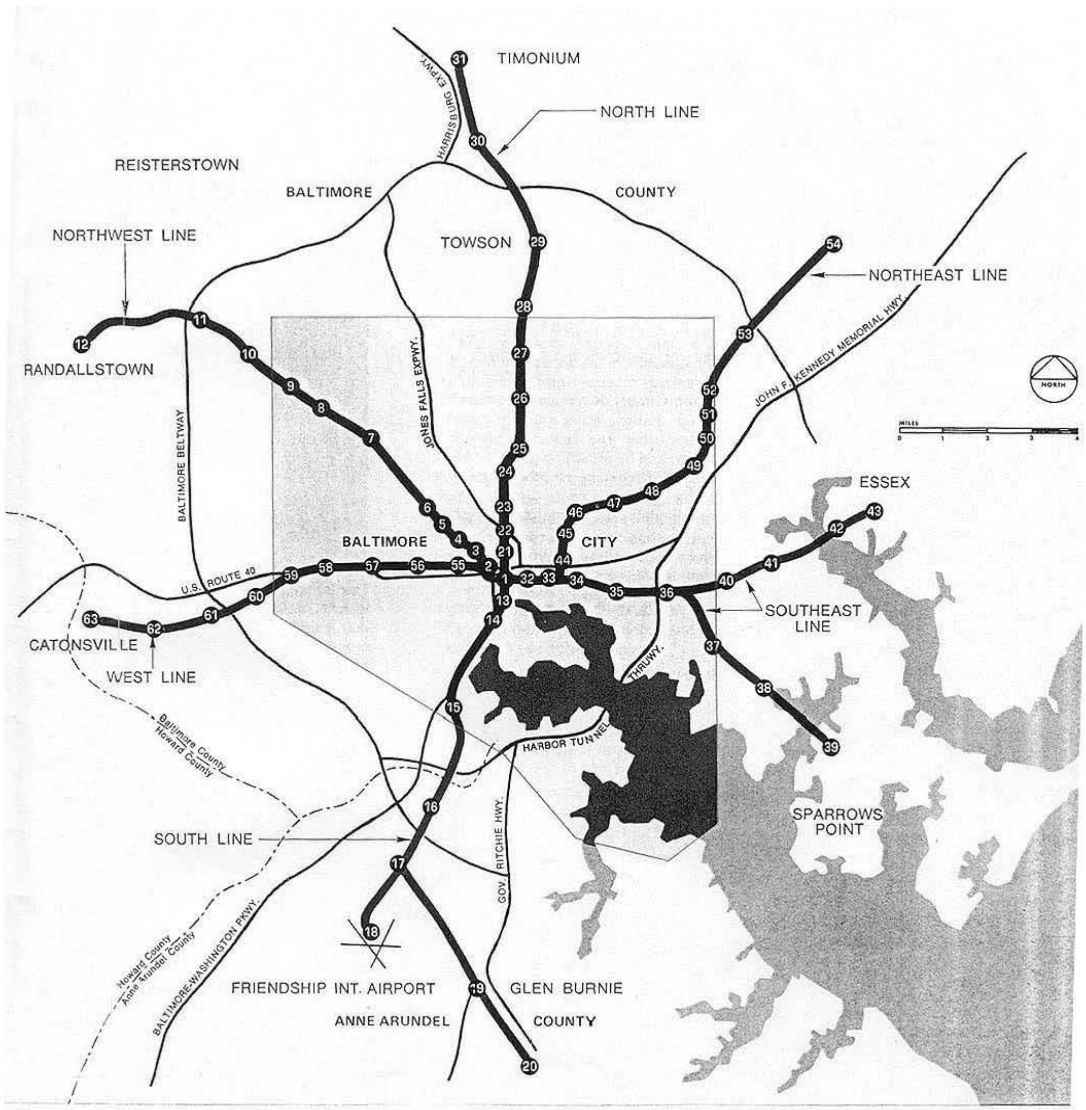
The Baltimore MTA continued to explore rail transit alternatives into the mid-1980s. As the MTA studied potential light rail alignments north and south of Baltimore, Mayor William Donald Schaefer was leading a successful campaign to revitalize downtown and was performing equally well statewide in a run for governor.

Named "the best mayor in America" in 1984 by several national news magazines, Mayor Schaefer was spearheading initiatives that led to a new convention center, hotels, businesses, and the magnificent National Aquarium.

While the city was making strides, it also had its share of setbacks. That same year, the National Football League's (NFL's) Baltimore Colts moved out of town in the dead of night, an event that disappointed many in the community, perhaps none more so than Schaefer. Following that event, the mayor worked tirelessly for a way to keep Major League Baseball's Baltimore Orioles in town while luring a new NFL team. The idea of a new stadium in Baltimore had a tough time gaining traction in the state legislature.

But when Mayor Schaefer became Maryland's 58th governor in a landslide victory in 1986, the timing proved propitious for the city's professional sports ambitions, as well as the MTA.

As Gov. Schaefer shepherded a proposed baseball stadium through the state legislature, he became aware that the MTA had studied a potential light rail alignment passing within a block of stadium's preferred site, Camden Yards, which had long held significance as a major passenger and freight rail hub but that fell into disuse with the rise of air travel and the decline of interstate passenger rail service. So, in 1987, with plans to construct Oriole Park at Camden Yards becoming a reality, Gov. Schaefer instructed the MTA to build a light rail system to serve the stadium by opening day.



-1. Baltimore Region rapid transit system routes and station locations.

FIGURE 1 1968 map of the envisioned Baltimore Region Rapid Transit System, prepared for the Mass Transit Steering Committee, Regional Planning Council, Baltimore, Maryland.

With a projected grand date in 1992, the MTA knew that a federally-funded project would not go from conceptual study to revenue service in under five years, but Schaefer was not swayed. He ultimately decided that the light rail system would be built without federal funds to accelerate the schedule, and he instructed MTA to proceed.

CREATING THE CENTRAL LIGHT RAIL LINE STARTER SYSTEM

MTA began designing the light rail system, to be called the Central Light Rail Line (CLRL), in earnest June 1988. The initial line would run from Timonium (north of the city in Baltimore County) to Glen Burnie (south of the city in Anne Arundel County) with an at-grade alignment, except for a bridge over the Middle Branch of the Patapsco River just south of downtown Baltimore. In June 1989, Oriole Park at Camden Yards broke ground. To the credit of all involved, both construction jobs met their deadlines, and the 22.5-mi light rail system running between Timonium Station and Cromwell Station was operating, and fans were able to ride into Camden Yards Station for the Orioles' opening day April 6, 1992 (Figure 2).

As one can imagine, a system designed and built in less than four years without federal funding needs to be built with cost containment initiatives in place. Yet the CLRL was over budget from the get-go. Unfortunately, when establishing the original system estimate of $190 million, it was hastily developed based on conceptual information. When the first official estimate for a no-frills system was received during the preliminary design phase, it was $400 million. Based on prudent, additional value-engineering efforts by MTA, engineering consultants, and the construction companies, the starter system was designed, managed, and built at a final budget number just shy of $365 million.

Designing with No Frills

The CLRL was designed and built using numerous accommodations that achieved cost-savings over an optimally implemented system:

1. Early bidding: Construction contracts were put out for bid prior to the completion of 100% design. This placed budget risk on the MTA due to potential changes. Ultimately, this decision bore out favorably for MTA and resulted in time-savings that translated into cost-savings.

FIGURE 2 MTA Camden Yards Station.

2. Single-track sections: The decision to single-track portions of the line was not made easily. MTA fully understood the operational and service limitations of single-track operations:

- Longer travel times due to the need to wait for trains in the opposite direction;
- Less frequent service resulting in a less convenient, attractive service;
- Lower passenger capacity due to less frequent service, not allowing for future ridership growth; and
- Reduced overall operational and maintenance flexibility.

In the end, MTA established that the line would operate under an acceptable schedule of 15-min headways. As a result, the line was constructed with seven sections, totaling 8.2 mi, of single-track line. Bridge substructure was designed and constructed to allow a future second track; however, no additional accommodations were put in place for such a future upgrade.

3. Power system: The CLRL did not include a robust power distribution system along the right-of-way. Rather, it was implemented using local power feeds and connections.

4. Signaling system: The line went into revenue service using fully manual operation and a fixed block signaling system. There was no onboard automatic train protection, and operators were fully responsible for speed adherence and stopping.

5. Basic control center: MTA chose not to implement a computer-based central control center. The line went into revenue service with a simpler, manual control center that operated with a chalkboard and radio communications between dispatchers and the vehicle operators.

6. Storage yard: The light-rail vehicles were stored in a single-ended storage yard with unpowered turnouts. This implementation increased staffing requirements for yard operations but reduced the system cost.

COMPLETING INTERMEDIATE UPGRADES

Three extensions to the CLRL began construction in July 1995. A 4.5-mi-long northern extension ran from the existing Timonium Station to Hunt Valley and included five stops. It opened in September 1997. A 0.34-mi Penn Station extension and a 2.7-mi Baltimore-Washington International (BWI) Airport extension both opened that December.

The Penn extension connected directly into the platform level of Penn Station, providing a direct link to Amtrak and MARC Train Service, a commuter rail line serving Harford County, Baltimore City, Brunswick, and Frederick, Maryland; Washington D.C.; and Martinsburg, West Virginia. The BWI extension ran directly into the airport's international terminal, placing travelers within walking distance of all flights.

These extensions cost $106 million and utilized a single design–build contractor. Combined, they were one of the five such efforts across the country recognized by the FTA in what was termed as a "Turnkey Demonstration" program.

In 1998 the Hamburg Street station opened adjacent to M&T Bank Stadium to support traffic during Ravens games and other stadium related events.

Limitations of a Single-Track System

With these small but important extensions, service requirements increased, highlighting the limitations of the existing single-track system.

The original light-rail track configuration allowed trains to proceed at 15-min intervals, also known as headways, in each direction between Timonium and Cromwell Station in Glen Burnie, providing shuttle service between BWI and Linthicum Station. However, once through service between Penn Station and BWI was established, the infrastructure could not support the original 15-min headways.

The greater number of train trips on the system also meant that trains traveling in opposite directions were meeting more frequently at various locations along the line, close to the single-track section entrances. These meetings forced the MTA to lengthen the headways from 15 min to 17 min to allow time for the single-track section to clear. As a result, the MTA had to reduce the frequency of service north of Mount Royal and south of Linthicum, but it also had to forgo the schedule convenience of service at regular 15-min intervals on the hour. Overall those changes meant less flexibility for MTA and more waiting for riders.

DOUBLE-TRACKING THE CLRL

In 1997 MTA commissioned a feasibility study to develop a cost estimate for upgrading the CLRL to a double-tracked system (Figure 3). The study evaluated the eight single-track sections as well as upgrades to improve headways, reliability, flexibility, and safety. Based on the concepts recommended in the study, the unescalated program cost estimate was $175 million.

MTA took the upgrade project through the environmental, engineering, and grant process, and the first construction contract for the Middle Branch Bridge was awarded in March of 2002.

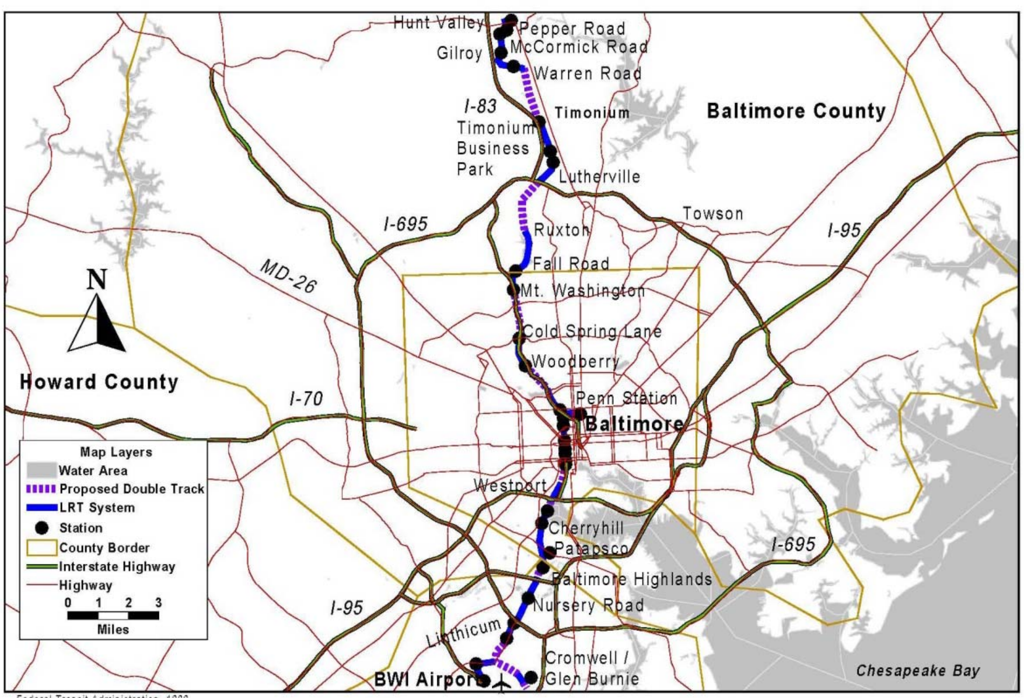


FIGURE 3 MTA double-tracking project map.

Upgrades, Replacements, and Other Work

The CLRL Double Tracking Project was funded primarily by the FTA under the provisions of the Transportation Equity Act for the 21st Century and a local matching share provided by the Maryland Department of Transportation. There were five primary goals in designing and constructing the double-tracked light rail service:

1. Enhance system reliability, thereby improving service to existing customers and attracting new customers;
2. Reduce the minimum possible operating headway from 17 min to 8 min;
3. Improve the effectiveness of Cromwell Station as a terminal;
4. Allow operations recovery in case of service disruptions; and
5. Allow access to track during off-peak hours for maintenance, resulting in an easier and more cost-effective maintenance program.

Primary upgrades included the following:

- Track configuration and civil engineering: A second track was added in the single-track sections to create a continuous double-track system. The eight single-track sections were split between the northern and southern portions of the system, and some of the work involved shifting the original single-track section to accommodate the second track. In order to provide the maximum flexibility for the resultant double track system, MTA engineered it to allow reverse running on segments so track could be taken out of service without major disruptions to the operating system. MTA also evaluated the locations of existing track switches based on the planned, reduced headways and determined that relocation of some track switches was necessary.
- Bridges and structures: There were three bridges on existing single-track sections. New parallel bridges were constructed to accommodate the second track. As noted previously, the Middle Branch Bridge over the Middle Branch River (the longest structure, at 4,000 ft) was originally constructed with piles and pier caps in the over-water section to support both bridge decks (Figure 4).
- Station platforms: Four stations that were located in single-track sections (Mount Washington, Linthicum, Baltimore Highlands, and Cromwell stations) required a second platform.
- Signals: The original automatic block signaling system was replaced with a new cab signaling and control system with automatic train protection along the entire alignment except the central business district, where the trains operate under restricted speed condition within the street and no signaling system is provided except interaction with city traffic lights. The interlockings were redesigned to accommodate reduced normal-operating headways and to allow for 15-min single-track operational headways in case one track was removed from service due to emergency or maintenance requirements.
- Power distribution system: In order to increase operational reliability and flexibility, the traction power system was expanded (furnishing one new 2-megawatt substation and reinstalling three existing 1-megawatt substations) to handle additional load requirements. Sectionalizing switches in the overhead contact wire were added at all interlockings to allow

FIGURE 4 MTA CLRL Middle Branch Bridge over the Patapsco River.

power to be shut off section by section. And, of course, catenary poles and contact wire were installed along all new track segments.

- Central control/communications: The existing central control computer servers and workstations were replaced, and an updated central control software platform was provided (Figure 5). Functional control capabilities were enhanced and updated to be consistent with the new power, communications, and signaling systems. The fiber optic system was extended to connect the new substations and interlockings, and an upgraded, ring-based wide area network was implemented.
- Vehicles: To complement the wayside signaling equipment, the full fleet of 53 vehicles was refitted with onboard equipment to support the new signal system and new communications systems installed throughout the CLRL. The volume of new onboard equipment was significant, requiring the railcar's original luggage rack to be converted into an equipment locker. Similarly, accommodating the various audible/visual/control components required trade-off considerations between ergonomics and a system that provided a holistic integration look and feel.

Scheduling and Costs

Because federal money hadn't been a part of the original line but was essential for the double tracking project, the National Environmental Policy Act environmental process had to be followed, wherein it was not followed under the phase 1 project. Therefore, it became clear that additional environmental assessments would be required, adding to the length of the project.

To complete the double tracking, south of downtown Baltimore a large portion of the line was shut down throughout 2004. The following year the line was shut down north of downtown, with the portion up to Timonium reopening that December and the remainder the next February.

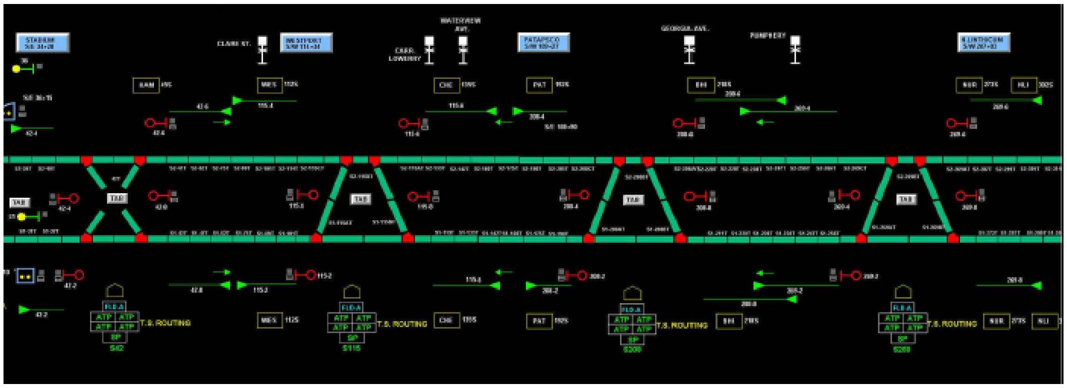


FIGURE 5 MTA CLRL central control overview display (partial).

This had a serious impact on the real and perceived reliability of the system, which experienced a decline in ridership that took several years to recover.

Despite the challenges related to operations and federal funding, local leaders believed that everyone's patience, while tested, would ultimately pay off.

"When the double track project is completed, we will have a light rail system that will be more reliable and flexible than ever before," said Maryland Transportation Secretary Robert L. Flanagan. "Our goal is to eliminate the bottlenecks on the system that create delays as one train has to wait to pass another. We are moving the construction along as rapidly as possible to complete the entire system and minimize the inconvenience to our customers. We appreciate their patience."

Constructed over a period of four years, with a final budget of $205 million and an FTA grant of $158 million, the double tracking program was completed in 2006 and has proven to be a great success. It reduced the minimum possible operating headway from 17 min to 8 min; provided access to the track during off-peak hours for maintenance, resulting in a simpler and more cost-effective maintenance program; provided greater operations recovery options in the case of service disruptions; and enhanced system reliability. Service was improved, and ridership ultimately rose from the range of 22,000–24,000 weekday riders in the years prior to the project up to 25,560 in 2008. As of the 2013 Annual Report, the average weekday ridership is 27,537.

GOOD NEWS FOR GROWING RAIL TRANSIT OPTIONS

As proven by MTA's experience with the CLRL, a rail system can successfully expand from a cost-constrained initial segment to a more-robust system. MTA was able to build and operate their initial light rail system for more than a decade, establishing ridership and encouraging economic development efforts, before funding was identified and available for adding a second track to much of the line's single-track sections.

There are costs associated with delayed implementation. The cost required to double track the line was greater than the amount saved initially. In addition, the service disruption had significant adverse impacts to passengers who had come to rely on the system (Figure 6).

Based upon MTA's experience, there are a few lessons learned that can be noted and shared for the benefit of other agencies considering a staged system implementation:

FIGURE 6 MTA CLRL operating over fully double-tracked alignment.

- MTA originally planned a multiple-phase construction sequence to minimize the overall impact on the revenue service but ended up with a relatively large shutdown along with bus bridges to enable the construction completion. Careful planning of rail segment shutdowns during the design and preconstruction phases can help minimize the overall system downtime.
- Try to anticipate future upgrades when designing initial segments. MTA's original rail line included installed piles and pier caps for the future second track across the Middle Branch River.
- Try to acquire right-of-way for future upgrades during the initial segment process.
- An environmentally controlled but rugged communication backbone is key to the success of a railroad communications, signal, and control system. Avoid specifying a vendor-specific technology, instead, require adherence to the industry standards for system equipment.
- Take advantage of the follow-on implementation to increase system availability through items such as back-up power, redundant equipment, and diverse communications paths.
- Installing onboard equipment onto revenue-operating railcars will require significant upfront planning to maximize seamless systems integration. Recognize that performing railcar equipment modifications on site at a transit agency (for example, in the rail yard or a maintenance shop) is much different in comparison to completing the same work scope in a

railcar builder's production facility; the early involvement of key operations and maintenance stakeholders is critical to realizing a successful execution phase.

- A key technical aspect of integrating new equipment into an existing system is to ensure the system safety for the modified system configuration. This effort can be mitigated to a significant degree by compiling the as-built documentation and confirming as-built configuration of critical components prior to initiating the system modification project.

Overall, and without doubt, MTA is pleased with its experience and hopes that its lessons learned can help other agencies mitigate costs and construction headaches in the future.

Denver Regional Transportation District's Central Rail Corridor Capacity Improvements

ERIC MILLER
Regional Transportation District, Denver, Colorado

The Regional Transportation District's (RTD) Central Corridor opened in 1994 as a demonstration line to test the viability of light rail in the Denver, Colorado, metro area. More than 20 years later, this relatively unchanged section, after corridor expansions, experiences more than 36,000 boardings each weekday, a peak-hour–peak-direction throughput of 4,600 passengers, and 20 trains per peak hour in each direction. With ridership continuing to rise, the RTD has taken steps to increase capacity with more planned.

The first two options to increase capacity on the Central Corridor failed partly because of budget constraints experienced shortly after the passing of the voter-approved FasTracks referendum in 2004. Peak capacity has been expanded in recent years by extending consist lengths to four cars on trains in an effort to meet service standards. Creative scheduling and a planned addition of a pocket track on the downtown loop will help balance the ridership demand.

With the above improvements, the existing system is meeting ridership demands and service standards on the strained original line. The current plan now being implemented will secure ridership capacity needed for new rail lines opening out of Denver's Union Station in 2016, although the future beyond that is not secure.

The future of the system relies on a proactive response to increased ridership demand. Without a significant amount of budget to put into physical improvements, an incremental approach has been applied and continues to move forward as a way to stay ahead of the curve.

CENTRAL CORRIDOR CONSTRUCTION

What eventually came to be known as the Central Light Rail Corridor was the result of more than two decades of studies, or "analysis paralysis," for some form of fixed guideway rapid transit system that began when the RTD was formed in 1969. For almost a decade after the failed rapid transit projects of the mid-1970s, which were to bring heavy rail transit to Denver with federal funding, the RTD board stance was antirail with a focus on growing the bus network and planning rapid bus corridors (Figure 1). Change in RTD board leadership and a renewed interest in rail transportation from the State of Colorado led to a new direction in the late 1980s (Figure 2).

In May 1987, the Colorado General Assembly passed House Bill 1249, which directed the RTD to develop plans for rapid transit in seven corridors in the Denver metropolitan region. This included more than 60 mi of rapid transit corridors in the first phase of construction. In 1989, the board identified one major route segment that could be built with available funds: a light rail line between Stapleton International Airport and downtown Denver. This led to the 1990 Northeast Corridor Alternatives Analysis Study. The corridor length was 7.5 mi (12.07 km)

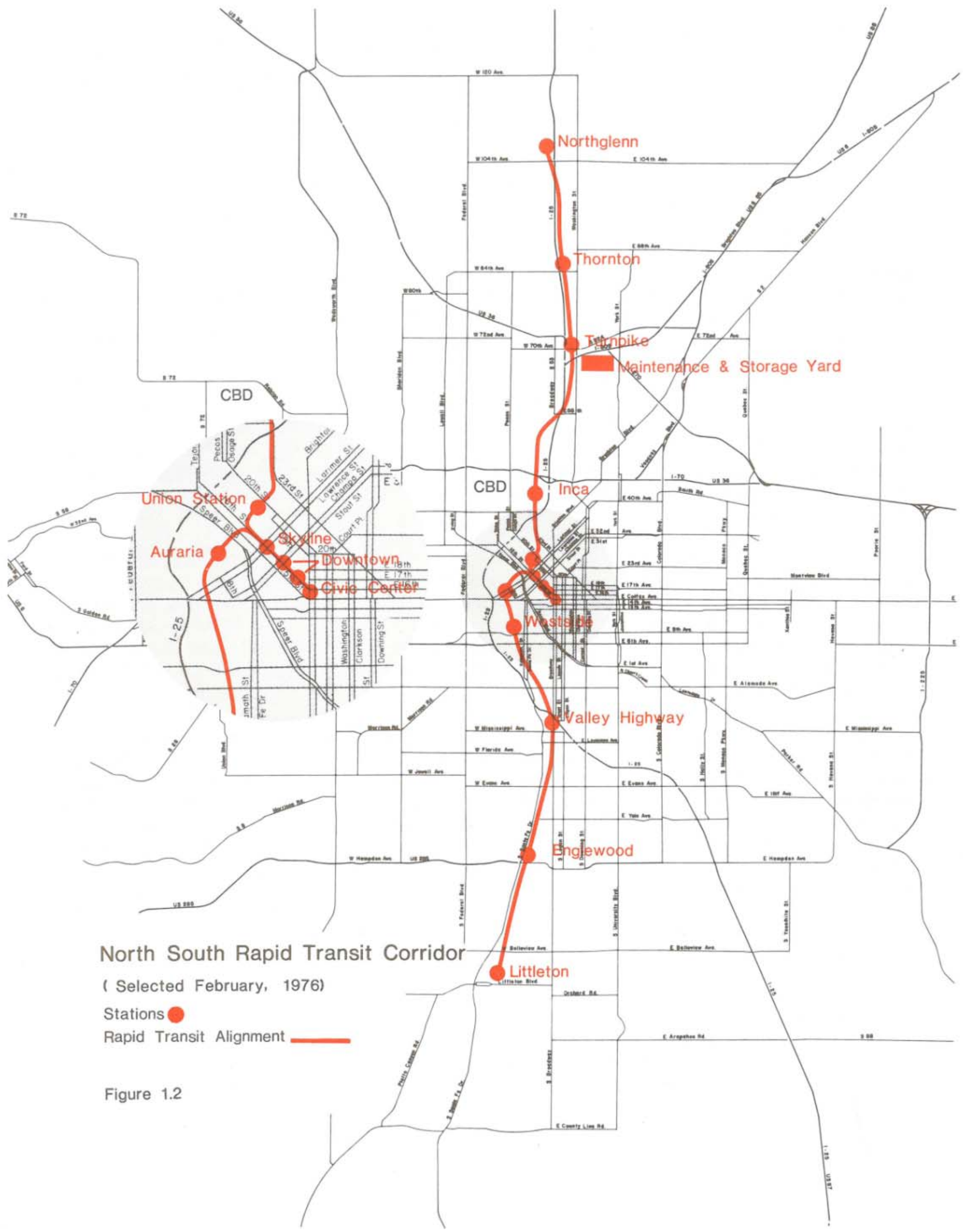


FIGURE 1 North–South Rapid Transit Project as of 1976: an example of a failed large rail transit proposal.

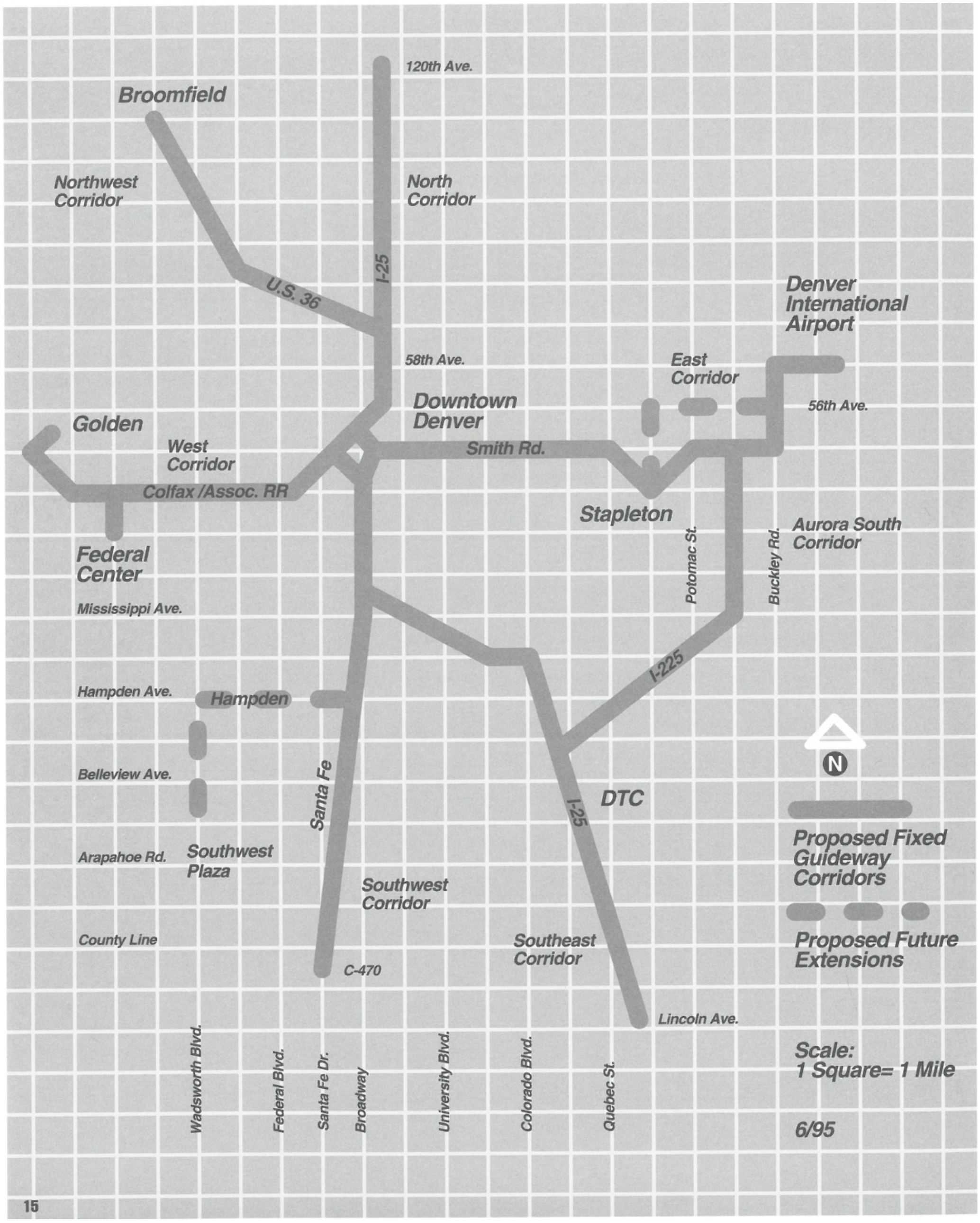


FIGURE 2 Regional rapid transit plan approved by the RTD board of directors in 1987.

with an estimated running time of 25 min from end to end; 10-min peak headways and 20-min off-peak headways were planned (Figure 3). As a result of the study and the community involvement process, the proposal for running in the landscaped median of Martin Luther King Boulevard became too controversial, and the project was cut back to terminating at 30th Avenue and Downing Street (Figure 4). Alternative routes to the airport were either too costly, also controversial, or had too little potential ridership.

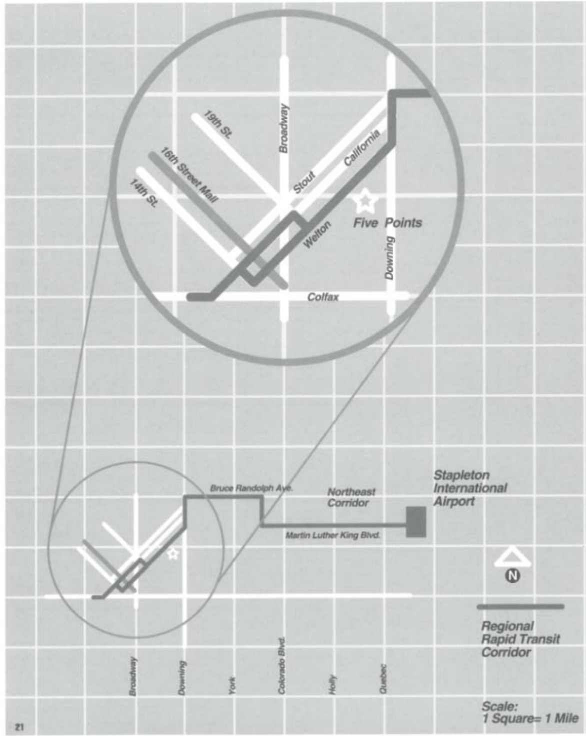


FIGURE 3 Northeast Corridor [(7.5 mi (12.07 km) long] from the alternatives analysis study in 1990.

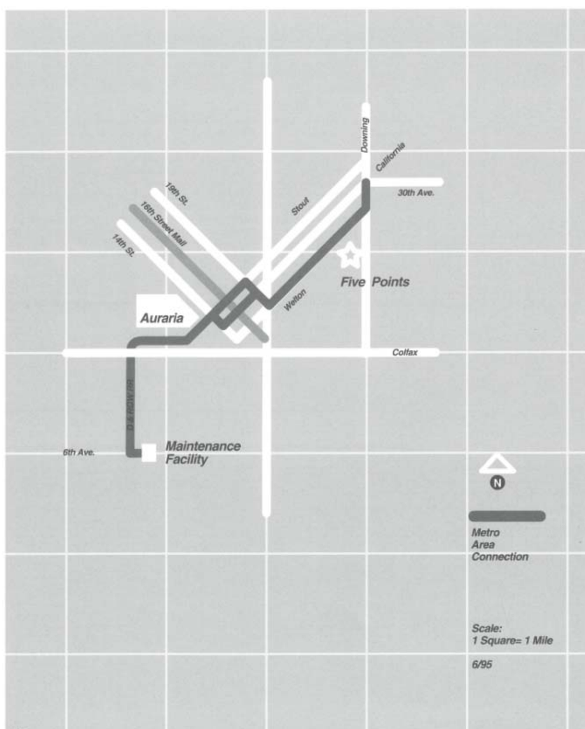


FIGURE 4 Condensed Central Corridor as a result of public involvement.

The new Central Corridor project had a length of 2.1 mi (3.38 km) between 30th and Downing and the Auraria Higher Education Campus west of downtown Denver, with a short distance south of the campus to a maintenance and operations facility. This was planned to operate at 5-min peak headways and 10 min off-peak headways and was funded entirely by an existing use tax that was earmarked by the board in 1987 for rapid transit. The projected capital cost in 1990 dollars was $70 million, as well as an operations cost of $2.44 million, annually. Ridership was projected at 4,600 average weekday for the opening year and 9,900 in 2010 or 73,300 for the full build-out of the entire rapid transit system (all seven rapid transit corridors).

On July 17, 1991, the Denver Regional Council of Governments (DRCOG) approved construction of the starter line. At this vote, there was majority recognition that 20 years of giant projects had failed to get off the ground, and this demonstration line would be the central portion of the overall planned system. Some DRCOG members were concerned that the ridership forecast would not make a dent in the region's overall transportation problems and had asked why the line did not continue south on a proposed corridor (Figure 5).

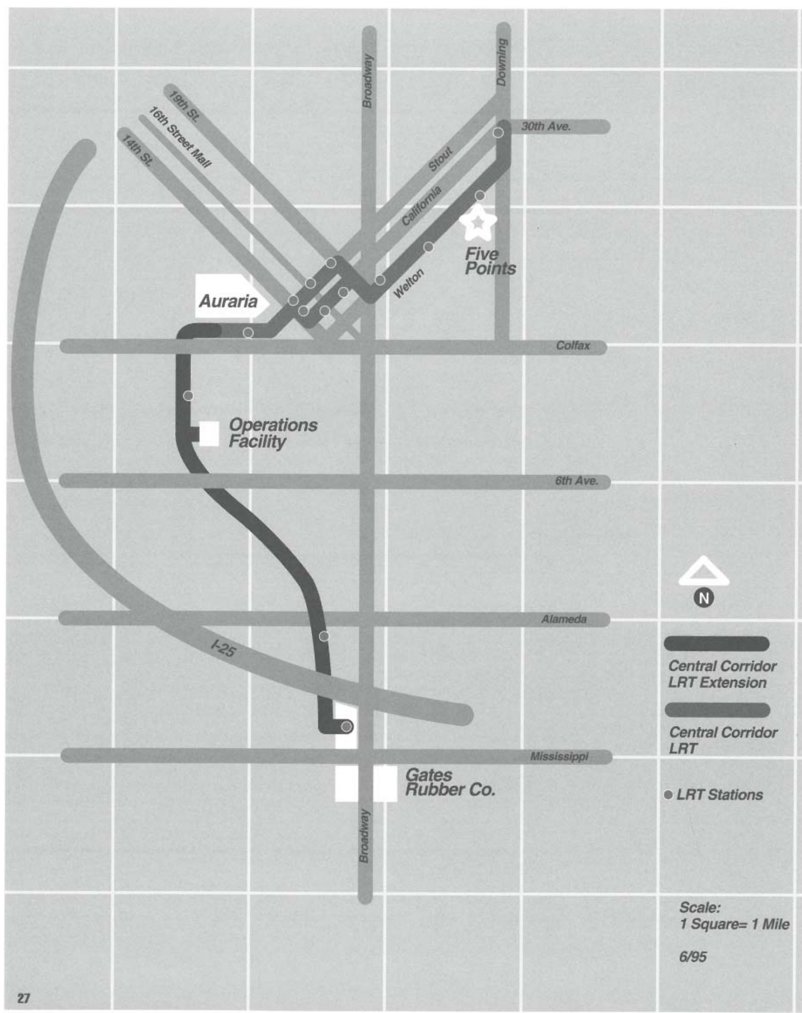


FIGURE 5 Proposed South Extension to the Central Corridor as of 1992.

At this time, the project was renamed the Metropolitan Area Connection, or MAC. Just after the Martin Luther King Boulevard controversy abated, criticism began to increase about the portion that would use Welton Street through the Five Points business district to the 30th and Downing terminal for which a bus transfer center and Park-n-Ride were planned. The compromise was to single track the eastern third of the line, which would reduce parking impacts on the businesses along Welton Street.

This led one board member to request that RTD staff look into the feasibility of extending the line south through a common portion shared by two officially adopted corridors: Southwest and Southeast (Figure 6). The RTD service planning staff were instructed to look into the feasibility of altering bus service to the light rail at the south end, which had potential to save huge amounts of operating costs from not having to run through downtown while increasing the light rail ridership.

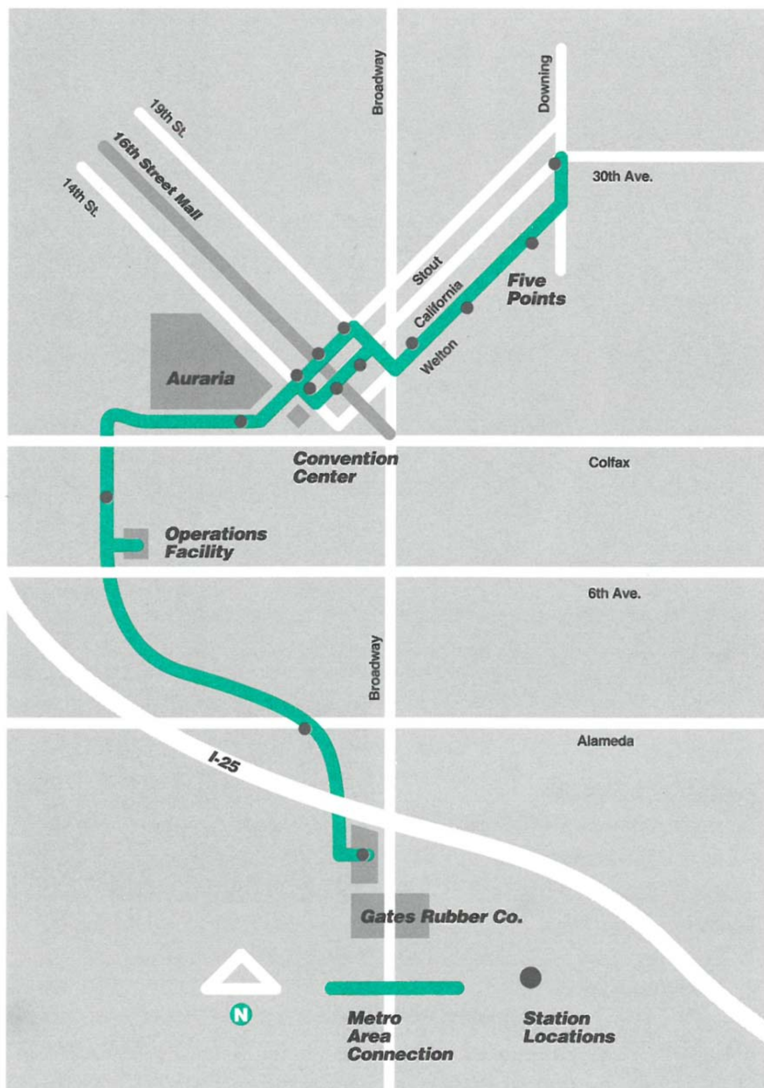
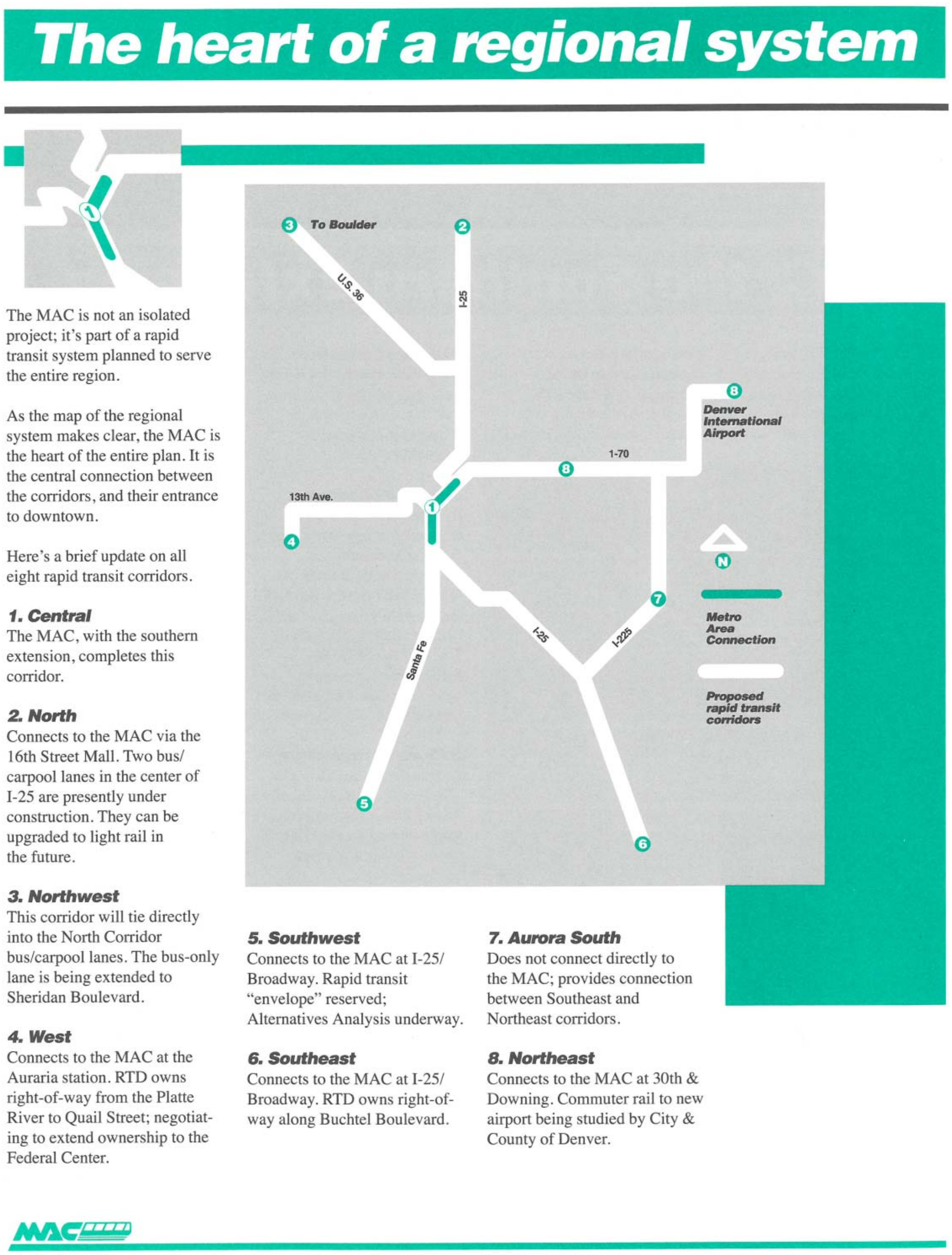


FIGURE 6 Full 5.3-mi (8.53-km) MAC alignment with proposed Southern Extension in 1992.

The savings were estimated to be 500 bus trips and 26 peak buses in addition to an additional 8,000 bus riders who would be diverted to the light rail line. At the same time, the maintenance facility site was moved further south and past a planned future station site at 10th and Osage. Another bonus was that the RTD already owned the property to the south station site. In April 1992, the board voted to proceed with planning the south segment. The $32 million South Extension was funded by a bond purchased through future operational cost savings (Figure 7).



The heart of a regional system

The MAC is not an isolated project; it's part of a rapid transit system planned to serve the entire region.

As the map of the regional system makes clear, the MAC is the heart of the entire plan. It is the central connection between the corridors, and their entrance to downtown.

Here's a brief update on all eight rapid transit corridors.

1. Central
The MAC, with the southern extension, completes this corridor.

2. North
Connects to the MAC via the 16th Street Mall. Two bus/carpool lanes in the center of I-25 are presently under construction. They can be upgraded to light rail in the future.

3. Northwest
This corridor will tie directly into the North Corridor bus/carpool lanes. The bus-only lane is being extended to Sheridan Boulevard.

4. West
Connects to the MAC at the Auraria station. RTD owns right-of-way from the Platte River to Quail Street; negotiating to extend ownership to the Federal Center.

5. Southwest
Connects to the MAC at I-25/Broadway. Rapid transit "envelope" reserved; Alternatives Analysis underway.

6. Southeast
Connects to the MAC at I-25/Broadway. RTD owns right-of-way along Buchtel Boulevard.

7. Aurora South
Does not connect directly to the MAC; provides connection between Southeast and Northeast corridors.

8. Northeast
Connects to the MAC at 30th & Downing. Commuter rail to new airport being studied by City & County of Denver.

FIGURE 7 How the MAC fits into the planned regional rapid transit system.

Construction downtown began on July 6, 1992, with work to move a water main and other utilities. The maintenance facility started construction in September 1992. The DRCOG approved the south segment on October 21, 1992, with a vote of 29 to 5. The expectation was that the south part of the project would catch up because it was on open, former railroad land through a mostly industrial area. The new opening day ridership projections were set at 13,000 average weekday passenger trips. The revised project was 5.3 mi (8.53 km) in length, and the new southern terminus at I-25 and Broadway Station would provide transfers to 29 bus routes.

Start-up operations required 10 light rail vehicles to run in service with alternating trips from I-25 and Broadway Station to and from 19th Street and 30th and Downing. An 11th vehicle was used as a spare. The board approved an order for six additional light rail vehicles in late 1994. The operational cost savings of the South Extension amounted to $2.3 million per year and $0.76 million per year in bus capital costs.

OPENING OF THE CENTRAL CORRIDOR AND INITIAL OPERATIONS

The Central Corridor opened on October 7, 1994. Ridership was up to 16,118 average weekday boardings in 1999, the last year of operation before the first extension, which is 50% higher than the 2010 projection. The ridership response is a testament to the vision exhibited by transit leaders in the early 1990s that a demonstration line could not only show the public what rail transit is like but also be very successful as a stand-alone line as well. This success would continue in the years to come as extension studies that were underway when the Central Corridor opened would be constructed and complement the starter line.

Initial operations on the Central Corridor were relatively simple. The design easily met the burdens of the service provided and also had adequate capacity for the ridership demand. The advantage of building the first rail transit corridor in Denver on a shoestring budget that was entirely financed by the transit district is that the momentum started for building out the full regional system. The disadvantage is that as more corridors were opened and more service was placed on the original line, the cheaply built line faced some serious upgrades beyond normal state of good repair maintenance.

Two primary projects helped with the future capacity issue, and the RTD had the foresight to start on these early before ridership demand became an issue: the Central Platte Valley (CPV) Extension and the Central Connector study. The CPV Extension was mainly a response to a shift in a new direction in the late 1990s as the Denver Union Station (DUS) was available for the RTD to purchase, and this was seen as a great potential for use as a future downtown multimodal station. The CPV Extension, while introducing a flat junction to the system, opened up capacity for more trains going to and from downtown because there is limited capacity running trains through downtown on the original loop. The other project was begun in advance of the Southeast Extension because that project would bring even more trains downtown and essentially max out the capacity of the Central Corridor. This project was considered the "third access" to the central business district (CBD) in that the CPV Extension would be the second access (Figure 8). It was part of the new FasTracks plan, which grouped the existing management information system and environmental impact studies into a rapid transit plan to be presented to voters in the future and built with an increase in the RTD sales tax. A previous plan called "Guide the Ride" failed in an election in 1997.

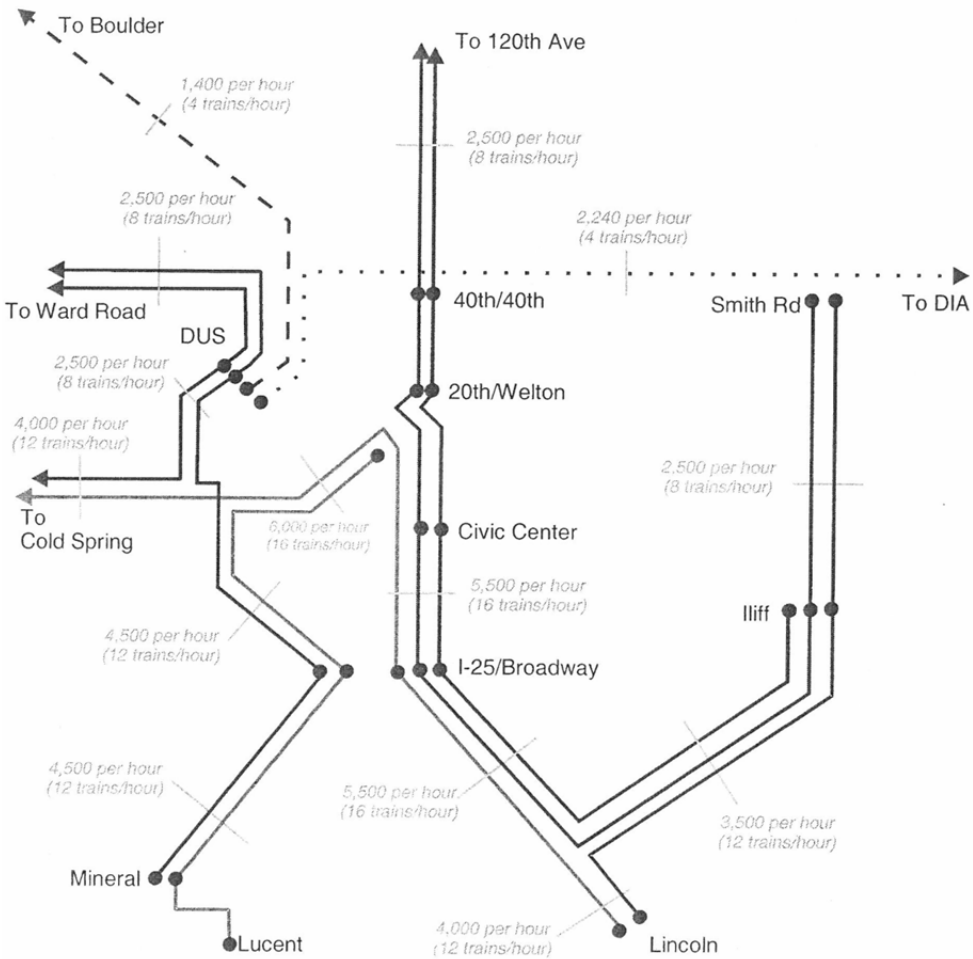


FIGURE 8 FasTracks rail line configurations with CBD third access peak period operation (DIA = Denver International Airport).

The CPV Extension was opened in April 2002, almost 2 years after the Southwest Extension. The operation was still fairly simple: the light rail was given letter designations with the original line from Mineral Station, the new southern terminal, to 30th and Downing as the D Line, and the new line to DUS became the C Line. In addition to serving DUS and its future potential, the new line served the major Denver region sport venues: Mile High Stadium for football and outdoor sports; Pepsi Center for basketball, hockey, and other indoor sports; and Coors Field for baseball.

The Central Connector Conceptual Feasibility Study started in the early 2000s and wrapped up in December 2002. The original rail alternative had a double-track line running straight north of the I-25 and Broadway Station, along Broadway or a combined Broadway–Lincoln pair, to downtown, serving the Civic Center area with its high concentration of employment that includes many government jobs. This would have diverted all the Southeast Corridor trains off the Central Corridor and on their own alignment into downtown, which complemented the Southeast Corridor service plan to replace many express bus routes that terminated at the Civic Center Station, an indoor bus transit center on the south end of the 16th Street Mall (Figure 9).

FIGURE 9 Central Connector Alternative 3A, the preferred light rail transit concept.

Similar to the Northeast Corridor study, the Central Connector study was met with resistance from neighborhoods and businesses who were concerned about having a rapid transit line running through their community, even though it would reduce most of the buses that traveled through there. Thus, the plan was scaled back from a solution to the growing rail network to a bus rapid transit alternative, which is essentially what the Route 0Ltd is running in the weekday peak periods today with meets at I-25 and Broadway Station for convenient light rail transfers. Instead, the RTD began to focus on improving the Central Corridor between CPV Junction (where the CPV Extension branches off) and increasing the capacity of this corridor. Enhancements were studied and included as part of the FasTracks plan.

IMPROVEMENTS PLANNED UNDER FasTRACKS

The revised FasTracks plan was placed before voters in November 2004 and won with 58% of the voters approving the sales tax increase (an increase of 0.4%, raising the total RTD sales tax to an even 1%), which would fund capital projects and the initial operations of the projects and sunset after approximately 40 years. Included in the plan was an engineering proposal to build capacity into the original Central Corridor between CPV Junction and I-25 and Broadway

Junction, which was the trunk of the light rail system and the major choke point for running additional trains. The proposal would have added two more tracks between I-25 and Broadway Junction to just north of Alameda Station and on the north side from CPV Junction to just south of 10th and Osage Station. The property required for the additional tracks was either already owned by the RTD or it was existing railroad property that could be negotiable. In addition, funds were allocated to partially grade separate the CPV Junction and assist with conflicting train movements that would add more capacity (Figure 10).

As part of the Southeast Extension, to mitigate the additional trains that would be running on the Central Corridor, part of this plan was implemented: a third track was built through the I-25 and Broadway Station that allowed a separation between southwest-bound trains and southeast-bound trains; this extra track is useful today for cross-platform meets late at night

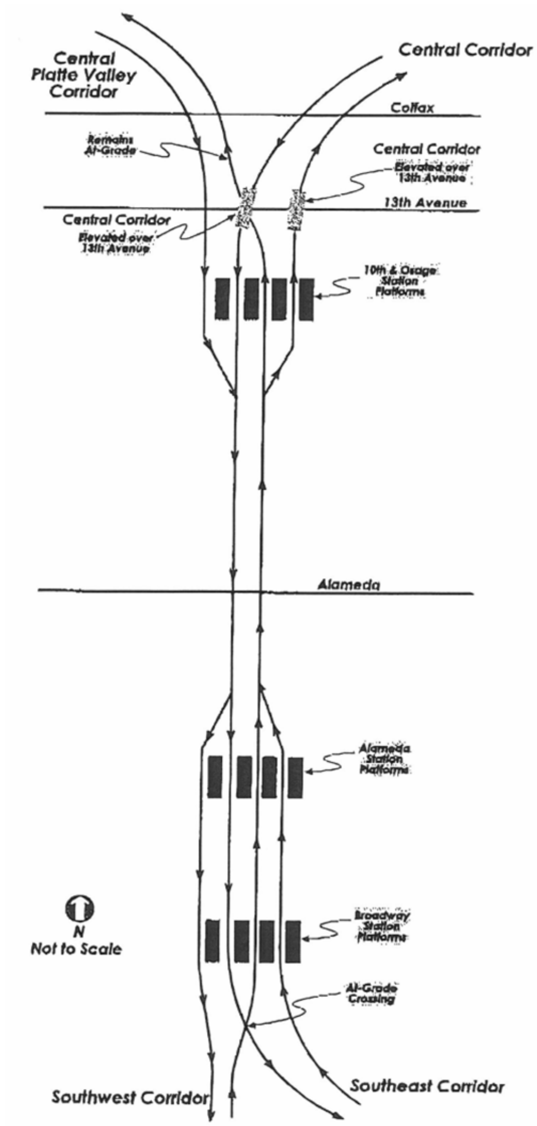


FIGURE 10 Central Corridor light rail operations improvements planned under FasTracks.

when there are reduced train frequencies. On the north end, a third track was built for trains going to the CPV spur so trains going to downtown could bypass a delayed train. The design was very similar to the south end of the trunk line, except there is no station involved. The Southeast Extension opened in November 2006 and nearly doubled the ridership of the light rail system (Figure 11).

After FasTracks passed in 2004, an unanticipated economic downturn now known as the Great Recession hit the country. The result for RTD's FasTracks program was that sales tax revenues decreased sharply, especially compared to what was expected to fund the program, and cost for construction materials went up. Each corridor was evaluated and pared down, and very creative financing methods were involved to keep some of the corridors afloat. In this process, the improvements to the Central Corridor were nixed.

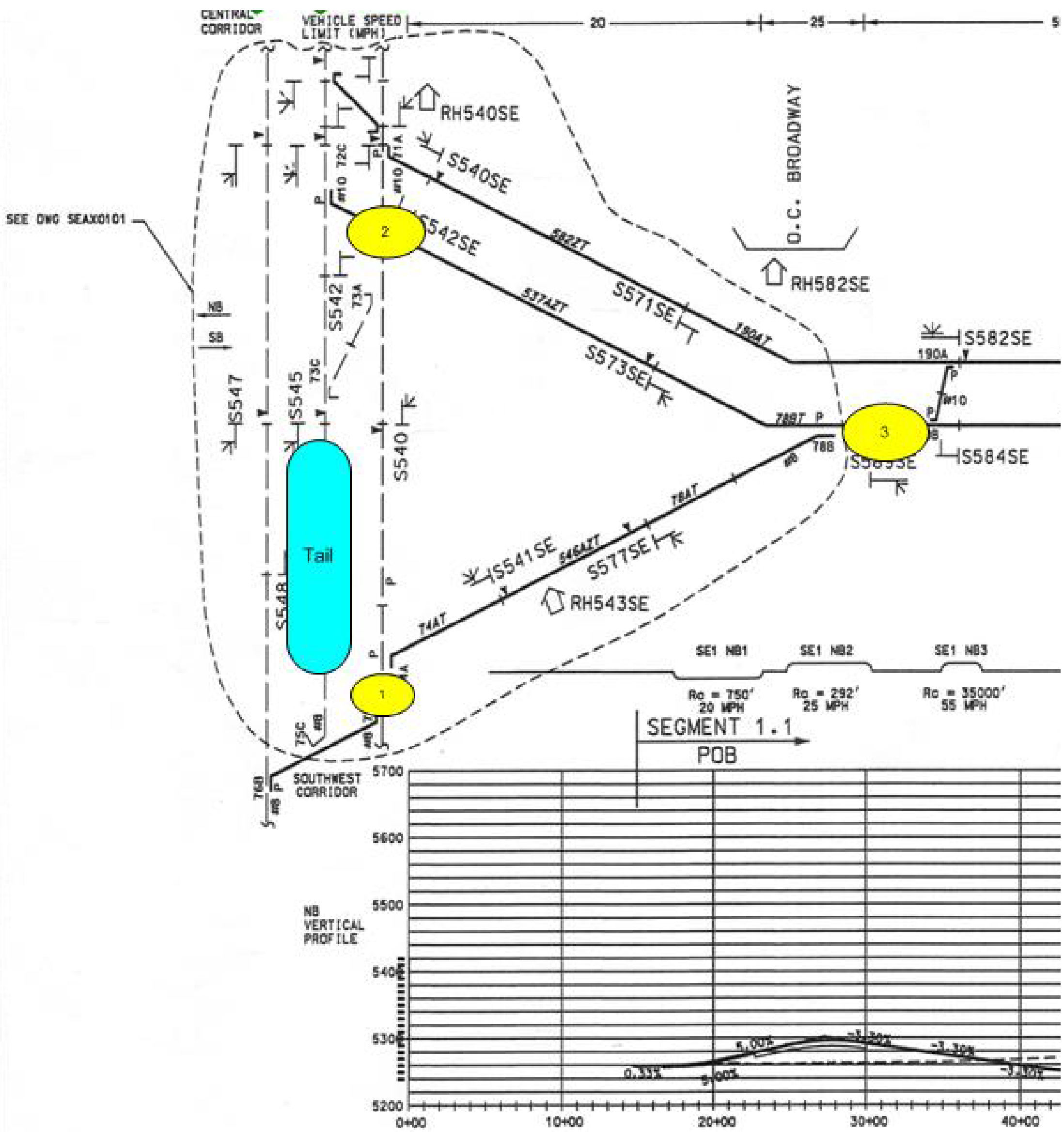


FIGURE 11 I-25 and Broadway Junction for the Southeast Extension, 2006.

IMPROVEMENTS UNDER AVAILABLE FINANCING

Without the Central Connector project and the improvements to expand capacity on the Central Corridor, small steps are being taken to improve critical parts of this corridor, an approach that has worked well for the RTD in the past.

More than 20 years after the Central Corridor was opened, this relatively unchanged start-up section experiences over 36,000 boardings each weekday, a peak-hour–peak-direction throughput of 4,600 passengers and 20 trains per peak hour in each direction. Average weekday boardings on the entire light rail system, as of the fall of 2015, is at 88,844, which are 15,000 more boardings than predicted for the full 1987 rapid transit system build-out. With the ridership continuing to grow beyond projections, the RTD has taken steps to assist with capacity in the original corridor and has more planned.

A major effort that required minimal track work that increased capacity on the system was upgrading station platforms to handle four-car light rail trains. This work was done in concert with adding traction power substations to handle the additional power and retiming the downtown Denver traffic signals so the longer cars could be accommodated through curves. The Southeast Corridor stations were all built with four-car platform lengths, so only the stations on the Central Corridor, Southeast Corridor, and CPV spur needed upgrading. A new station at the Colorado Convention Center that opened in November 2004 already had four-car platforms. The Welton Street segment was not able to handle this upgrade because of street restrictions. This constrains the D Line trains to and from 30th and Downing to operate with only a maximum of three-car trains and forces the need to run additional D Lines that loop through downtown during the morning and afternoon peak periods to handle the ridership demand between the Southwest Corridor and downtown Denver. With the ability to run four-car trains on most of RTD's lines, fewer trains were required to handle the passenger loads, which stabilized the capacity needs for the short term.

The existing light rail operation in the peak periods on the Central Corridor is running a train in each direction every 3 min. This equates to 20 trains per hour: six of these are trains to and from DUS, and 14 are trains to and from downtown Denver through the downtown loop. This was recently increased from 18 trains an hour after adjusting the schedule to allow for more frequent E Line service, which operates between DUS and Lincoln Station on the Southeast Corridor, one of the fastest-growing light rail lines. This is largely due to transfers with the new W Line as well as connections to other routes at the new Union Station bus concourse that opened in May 2013. With three commuter rail lines opening in 2016 (East, to the airport; Gold, west to Arvada; and the Northwest segment, beginning at Boulder), this line is projected to have even more increased ridership. Not far behind is the ridership increase on the C Line, the line between DUS and Mineral on the Southwest Corridor.

This is an example of how creative scheduling is used to counter a capacity issue: by running the lines to and from DUS more frequently, and spacing them strategically before trips that go to central downtown, this takes some of the strain off routes that would otherwise require an increase in frequency, which cannot be accomplished given the constraints on the Central Corridor. The current signaling system handles the 3-min headways well in that the minimum signal spacing is approximately 2 min, which gives a little buffer space for delayed trains. One of the next steps is to reexamine the signaling in this corridor, and the weakest link, the block just north of Alameda Station in each direction, has been identified as a priority to add another block and smooth the operation on this corridor.

Another FasTracks project has yielded some benefits to the Central Corridor: the Central Rail Extension, which is the extension of the light rail north of 30th and Downing Station to the 38th and Blake Station on the East Line. This is a 1-mi (1.6-km) extension using street-running double track along Downing Street. The operations plan for this extension, outlined in the Central Rail Extension Mobility Study, completed in 2014, is to run the line along Welton and Downing as a separate route, the L Line. Trains would loop through downtown and head northeast to a new terminal at 38th and Blake. This would help the rest of the light rail system by removing the single-track restraint from the D Line, allowing more appropriate shorter trains on this segment that could be low-floor vehicles and allowing the use of four-car trains on the rest of the D Line, which would terminate downtown (Figure 12).

The major obstacle for the Central Rail Extension is a needed space for trains to stage on the loop while waiting for an open slot to head back north. The study examined several different alternatives, looking closely at the area of 14th and Stout, where an existing wye is located. This was identified as the most cost-effective alternative in terms of capital and

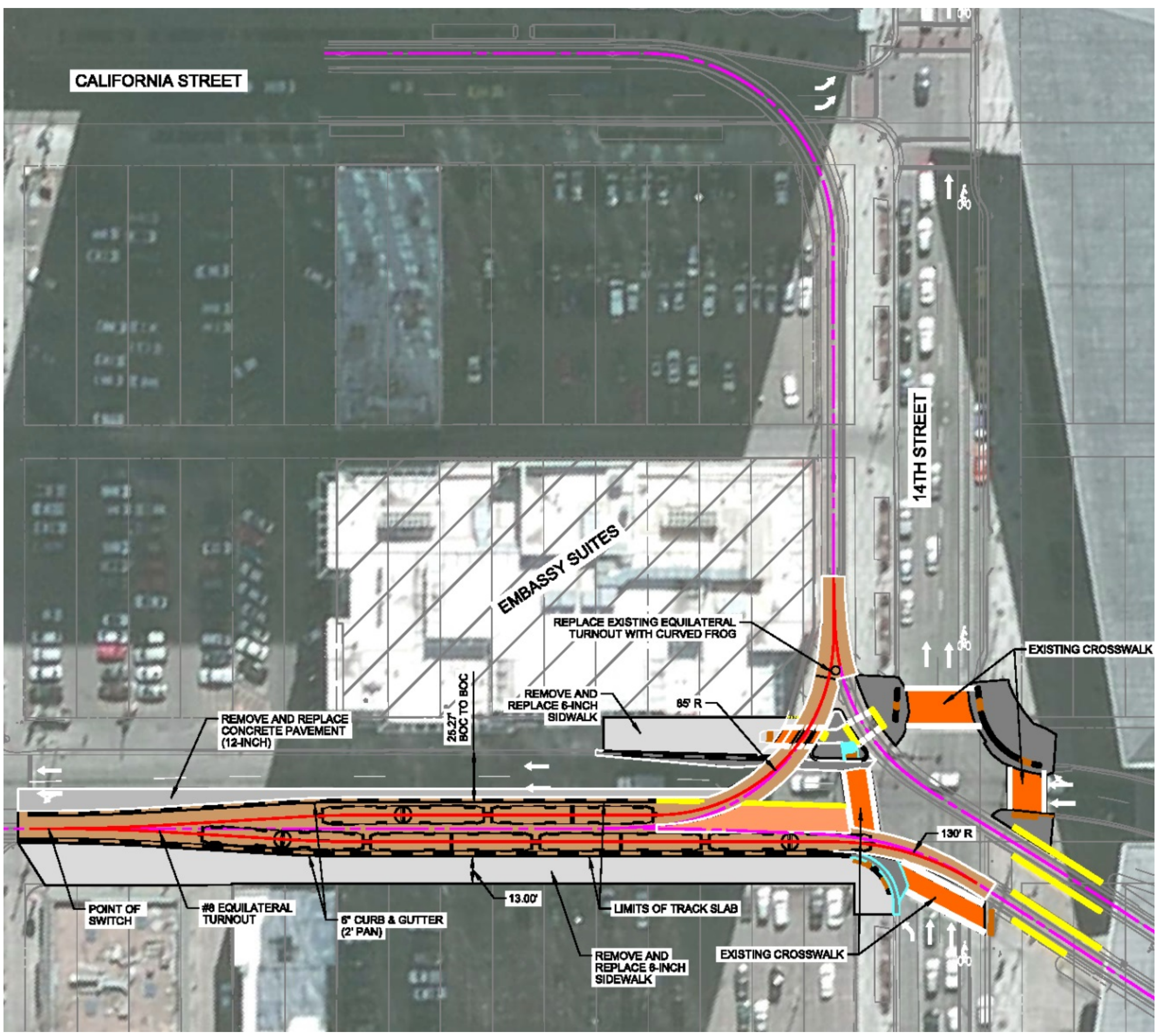


FIGURE 12 14th and Stout pocket track as proposed by the Central Rail Extension Mobility Study and included in the strategic budget plan for 2016.

operations costs. The pocket track is included in the annual strategic budget plan for 2016 but not forecasted to be funded until at least 2017. The rest of the Central Rail Extension remains in question without funding as of this paper. If the pocket track is constructed before the rest of the extension is funded, then the Welton Street segment could still be run as its own line, which would help the rest of the system. In this scenario, the additional peak D Lines would not necessarily be needed, and the slots in the schedule could transition to C Lines. (See Figure 13.)

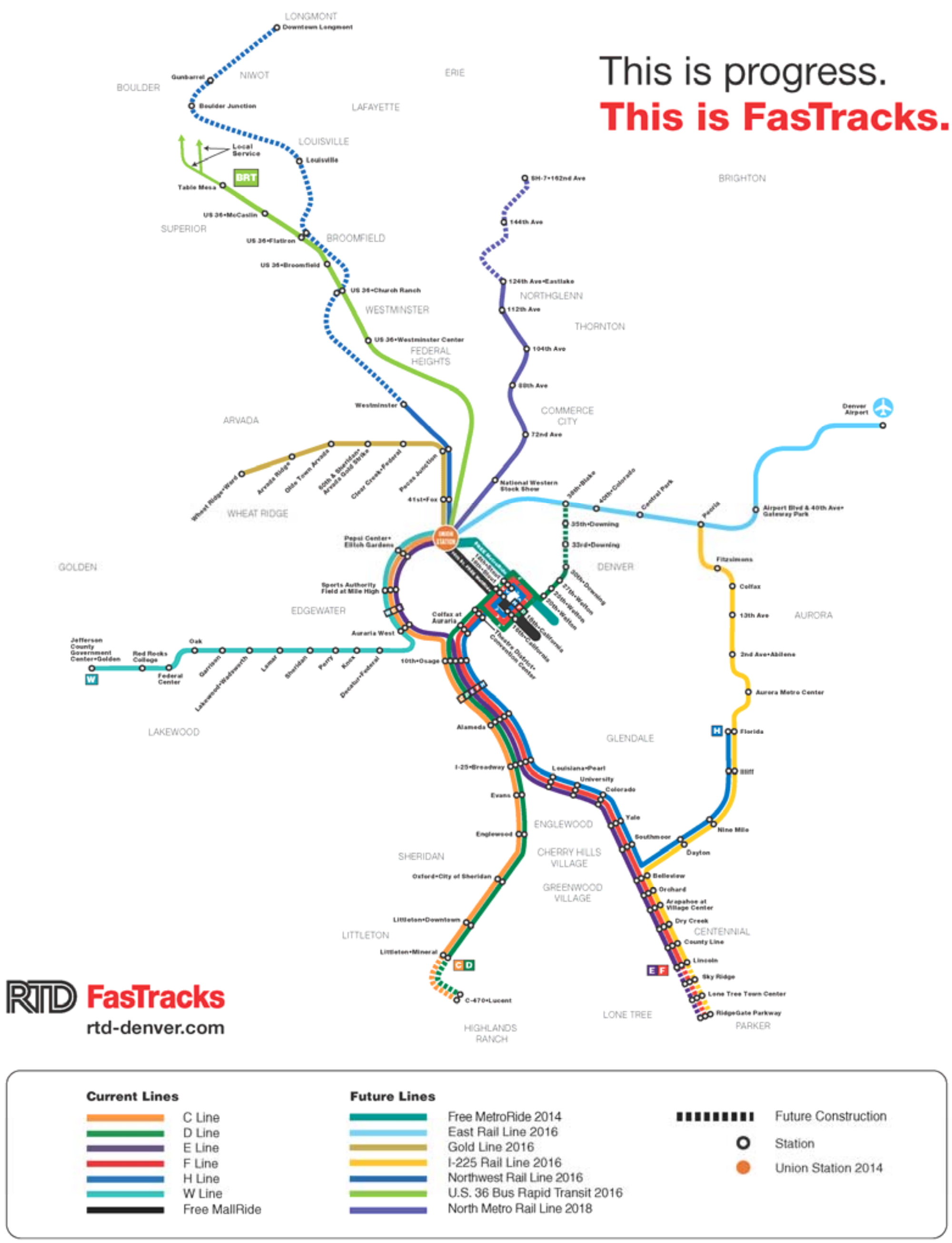


FIGURE 13 FasTracks system as currently being constructed.

These improvements will help the Central Corridor in the short term, approximately the next 5 to10 years. After that time, it will be worth reexamining the Central Connector or third access to the CBD in order to increase frequency on the growing Southeast Corridor trains. Another short-term idea that is being looked at by staff is constructing a pocket track north of the I-25 and Broadway Station to allow for additional trains to be run south of I-25 and Broadway without disrupting the operations on the Central Corridor. This would allow passengers to connect to the Route 0Ltd service to the Civic Center area. An extra peak-hour H Line train was operated from August 2014 to May 2015 to test the viability of this type of service for the future.

ACKNOWLEDGMENT

The author thanks Robert Rynerson, RTD service planner from 1985 to 2014 and friend and mentor, for providing much information on the history of the MAC line.

Compromise

A Necessary Element of Sacramento's LRT Starter Line

JOHN SCHUMANN
LTK Engineering Services

Sacramento, California, opened its 18.3-mi light rail transit (LRT) "starter line" in 1987, at a total initial capital investment of $175 million. The system as built was 60% single track, with simple stations, basic systems elements, and a fleet of only 26 light rail vehicles (LRVs). At just $9.6 million per mile, the project achieved the lowest cost per mile among new-start LRT projects built with federal funding, a feat no subsequent project appears to have matched. To achieve this low cost, several design compromises were necessary as compared with a fully double-tracked line furnished with more elaborate stations and systems and a larger fleet of LRVs. Since 1987, ridership has grown, the line has been improved and extended, and additional lines have added over 20 mi to the LRT system. Without the compromises made to kick-start the starter line on a low-cost basis, the project probably would not have been built at all, and regional transit today would still be a struggling all-bus system.

INTRODUCTION

On August 24, 2015, Sacramento Regional Transit opened its 4.3-mi South Line Extension to Cosumnes River College, the seventh extension since the original 18.3-mi starter line first began serving passengers in 1987. In celebrating this event, Federal Transit Administration acting chief Therese McMillan said the new service "will significantly improve transit options for residents traveling between downtown Sacramento and the growing South Sacramento corridor" (*1*).

Would any of this have happened had the decision to proceed been delayed to try and find more money to achieve a better initial project than the first bare bones line? Or would Sacramento have lost its opportunity for rail transit and remained a struggling all-bus operation?

The purpose of this paper is to summarize the 10-year gestation of Sacramento's initial starter line LRT project, from planning concept to operational reality, highlighting the interplay and important impacts of politics, public policy, and financial constraints that required planners and designers to adjust technical solutions, in effect "compromising" to achieve an effective LRT system within evident political and funding constraints.

GENESIS OF THE PROJECT: WHO WANTED LIGHT RAIL IN SACRAMENTO?

In the spring of 1975, two citizen transit advocates traveled from Sacramento to Philadelphia for the first Transportation Research Board light rail conference. As another writer put it, "the concept of the light rail idea was transmitted from this conference to Sacramento and, through the advocacy groups, gradually spread" (*2*). The same author opined that the LRT project eventually built was "not the result of a deliberately structured program…by government agencies," but rather "the result of a grass roots citizens' effort that took place in conjunction with two historic events." These events were the

- Availability of federal funding for public transportation infrastructure through an interstate transfer (i.e., authorization to move funds from highway to transit), a one-time opportunity using a program that was nearing sunset by 1980; and
- Rebirth nationally of the light rail idea in the mid-1970s and its strong reception by the administration of California Governor Jerry Brown.

A third factor essential to Sacramento's decision to proceed with an LRT project was that during the period of its formal planning, design, and construction (1977–1987), those viewed as pro-transit environmentalists dominated the region's two elected governments: the nine-member Sacramento City Council and the five-member Sacramento County Board of Supervisors. These two bodies appointed the seven members of the Sacramento Regional Transit District (RT) board of directors, who tended to take their cues from the elected officials who had appointed them.

As planning proceeded, three requirements emerged from state and local policy makers' deliberations, namely, that an initial LRT project should

1. Extend far enough to be of regional significance (i.e., not just a central area streetcar circulator; that had been studied circa 1976 and rejected in favor of a longer regional line[1]);
2. Serve the greater northeast area of the region by extending through both the Northeast and Folsom Boulevard (East) transportation corridors; and
3. Cost no more than the sum of the available federal interstate transfer funds and the minimal state and local matches necessary to secure them. It was anticipated that the funding would be 80% federal and 20% nonfederal, split 10% state and the remaining 10% divided among the city, county, and RT in whatever amounts each would contribute (*3*).

As a result of the alternatives analysis completed in 1981, it was determined that

- The two transportation corridors, US 50 and I-80, both served the same wedge of suburbia extending northeasterly from downtown Sacramento; and
- The preferred alternative should be an 18.3-mi LRT line (Figure 1) extending 9 mi from downtown along each corridor and operated as a single through-routed service (*4*).

DESIGNING AND BUILDING THE LRT STARTER LINE: GETTING IT DONE

Assertion: "The way a (rail) project works is: The engineers design the project; then the politicians find the money!"[2]
Aphorism: Don't let the perfect get in the way of the good.[3]

To those conceptualizing the Sacramento LRT project, it quickly became clear that the Seattle, Washington, Metro engineer's approach—full double tracking with all the associated technical bells and whistles—was not going to be feasible, but that instead it would be necessary

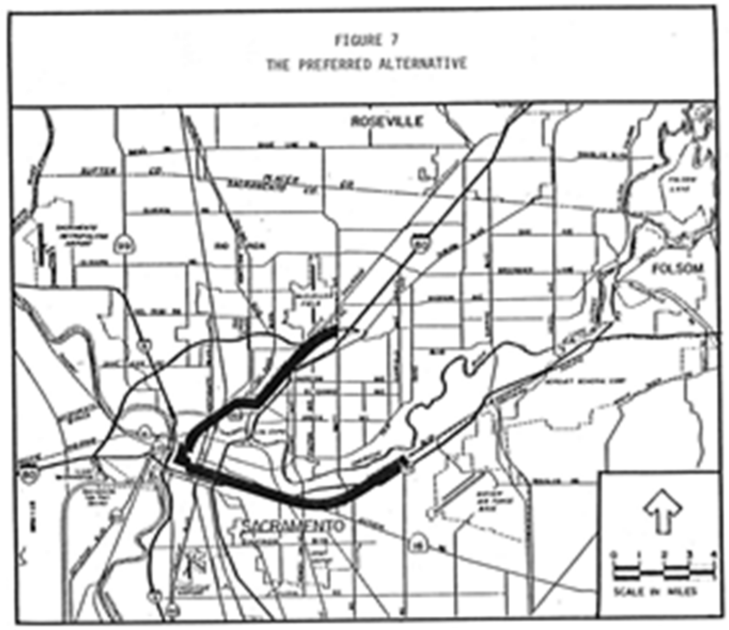


FIGURE 1 Preferred alternative: 18.3-mi LRT line.

to not let insistence on that "perfect" technical solution prevent doing something "good" for transit in Sacramento and to build it in a timely fashion so as to grasp the advantages of the moment: interstate transfer dollars, a friendly state administration, and pro-LRT local decision makers. Achieving this goal under the project's fiscal constraints required close adherence to a set of four key design principles:

- Use available rights-of-way,
- Limit the investment to facilities needed for a "starter" line,
- Employ proven off-the-shelf equipment, and
- Build for an efficient, no frills operation (*5*).

In fact, the design and sizing of the system were derived from the operating plan, which provides for a 2-h end-to-end round trip time, and eight trains offering 15-min headway service (*6*). Buses in Sacramento typically operated at intervals of 15, 30, or 60 min, offering a good fit with LRT arterial trunk service running every 15 min, and intermodal coordination at each of six key LRT stations designated as transit centers (Figure 2). Integral to the operating concept was that by using LRT to replace buses on the two trunks into downtown Sacramento, buses would be able to make two peak period trips on feeder routes in outlying districts (instead of a single through run all the way to downtown), with coordinated transfers minimizing inconvenience to transferring passengers.

Demand estimates indicated peak passenger flows could be accommodated by lengthening one- or two-car off-peak trains to rush hour consists of up to four LRVs, thus enabling peak operations to continue at the same eight-train 15-min base service headway. As a result, locations of meets between opposing trains would remain constant throughout the operating day. It became clear that even though planners, designers, and operating staff would have preferred a fully double-tracked line, the system nonetheless could be built with only 40% double track (Figure 3). This approach was essential to the overall concept: building the full 18.3-mi line, instead of having to truncate one or both of the two branches.

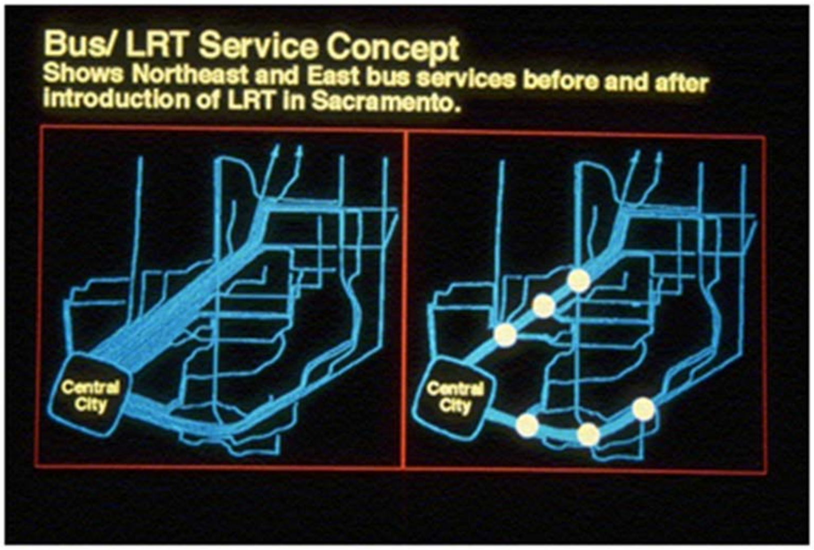


FIGURE 2 Multimodal, multidestinational system.
(Source: Sacramento NE Alternatives Analysis–Draft Environmental Impact Statement. Presentations & Working Papers, 1981.)

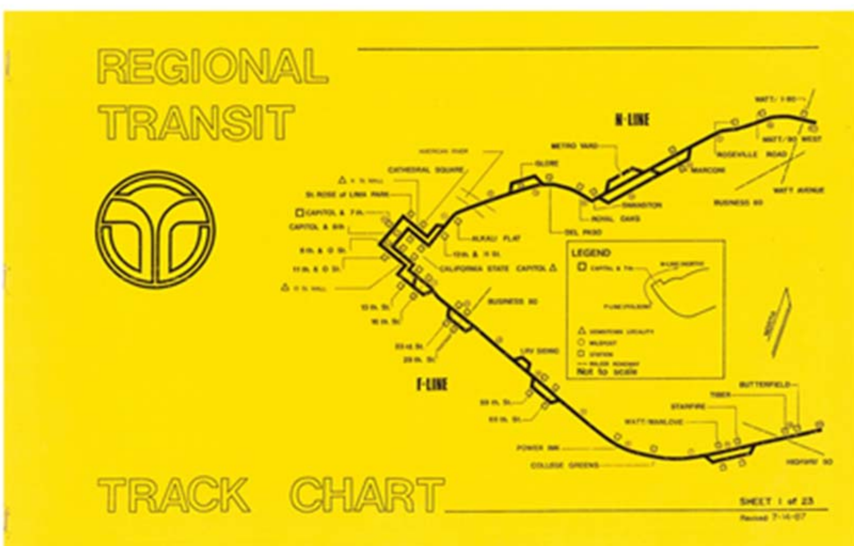


FIGURE 3 Northeast LRT starter line: track chart.
(Source: Sacramento RT Track Charts, 1987.)

Available rights-of-way tapped for the LRT line included former freight railroad branch lines (47%), excess freeway lands (25%), other private rights-of-way (2%), exclusive lanes in city streets (12%), two pedestrian malls (4%), and shared traffic lanes in city streets (10%) (*6*).

Emphasis was placed on designing limited-scope, low-cost fixed facilities, and specifying proven off-the-shelf vehicles and other equipment (traction power, signaling, voice radio communications, etc.) to provide a no frills system that would be buildable and operable within the limits of anticipated funding. The process followed was a careful assessment of all the project elements to determine what to leave in, and what to leave out, as compared with an idealized project.

When the starter line was completed in 1987, it had cost $175 million (Table 1), or $9.6 million per mile, and included track, rights-of-way, rolling stock, electrification, signalization, and urban amenities (*6*). This was and remains the lowest cost per mile of any federally funded LRT system in the United States. Other western U.S. LRT projects of the time cost on the order of 50% to 100% more. Only San Diego's initial LRT line, entirely funded with state and local monies to avoid the time-consuming federal project development process, cost less per mile to build.

Despite its modest capital investment, the project exceeded its preliminary engineering estimate by 34% (*6*). Except for the LRV procurement, increases were experienced in every major cost category. Despite lower-than-estimated bids for the first civil package of three highway overcrossing structures, higher-than-estimated bids were received for subsequent packages covering the LRV shop and yard, as well as line section contracts for track, station, and parking lot construction. Delays in completing the project led to higher-than-estimated expenditures for management and engineering.

TABLE 1 LRT Starter Line and Extensions

Project	Year Opened	Miles of Line		Comments
		Segment	System	
Northeast	1987	18.3	18.3	Starter line
Mather Field extension	1998	2.1	20.4	Folsom Corridor
South Line, Phase 1	2003	6.3	26.7	Second line[a]
Sunrise extension	2004	2.7	29.4	Folsom Corridor
Folsom extension	2005	7.3	36.7	Folsom Corridor[b]
Amtrak extension	2006	0.7	37.4	Downtown Sacramento, Gold Line
Downtown–River District	2012	1.1	38.5	Green Line, 30-min service
South Line, Phase 2	2015	4.3	42.8	To Cosumnes River College
DNA (future)[c]	tbd	12.8	55.6	Future line

NOTE: tbd = to be decided.
[a] Two routes: Blue (north–south) and Gold (Folsom Corridor).
[b] Mostly single track, 30-min service.
[c] Downtown–Natomas–Airport; likely to be built in two or three phases depending on funding.

WAS IT WORTH THE EFFORT?

When Sacramento's first LRT line opened in 1987 with limited bus–rail integration, passenger response at first was lackluster, but by 1990, when the planned interconnected rail and bus network had been put in place, LRT patronage grew quickly to the pre-revenue estimate of 20,500 weekday passenger trips and then continued growing over the next decade to about 30,000. As well, buses carried as many passengers as they had before LRT, and with the intermodal transit centers in place, the overall transit system became somewhat more convenient for nondowntown trips, even though RT's finances have been able to support little if any increase in bus service levels. Nonetheless, overall riding on the RT system grew from under 14 million annually in 1987 to over 28 million in 2000. LRT's contribution is efficiency on the main links, carrying 32% of unlinked trips and 39% of systemwide passenger miles, but using only 17% of the vehicle fleet, generating 22% of revenue vehicle miles while consuming 29% of operating expenses (2002 figures) (*7*).

IMPROVING AND EXPANDING LRT: MAKING A GOOD THING BETTER

The finished LRT starter line worked as planned. Trains achieved the planned one-way and round-trip running times with few glitches, even though outbound trains regularly paused a minute or so to wait for inbounds to clear single track sections at the north end of the central business district (CBD) and at the Arden–Del Paso intersection in North Sacramento, locations at which the City's traffic engineer had refused to allow double track. In East Sacramento, elimination of two passenger stations to assuage protesting neighbors led to trains making better time than planned. Both of these problems were overcome by additional construction during the 1990s: double tracking on North 12th Street and at Arden–Del Paso, which eliminated the pauses, and building the two "missing" stations as part of another double-tracking project, after the neighbors realized they wanted to be served by LRT after all. This slowed the trains a bit through East Sacramento so they now met the planned running times.

Even though the original project was 60% single tracked, nearly all of it was designed for eventual full double tracking,[4] anticipating that such work would be undertaken as funding became available in the years after opening. In fact, the improvements began almost immediately. Ten more LRVs were ordered when it was realized that four-car peak trains were needed in the Folsom Corridor as well as in the Northeast Corridor. The 36-car fleet made it possible to maximize the system's capacity, with eight four-car trains in service offering 15-min headway and four maintenance and reserve spares (12.5% spare ratio). Double-tracking projects started in1988 and continued. By 1992, the length of single track had dropped from 60% to 40% of the line (*8*).

Since then, seven extensions to the system have been completed (Tables 1 and 2). It may be observed that once the starter line was shown to be an effective addition to the region's public transport system, then subsequent extensions moved through the development and approval process more smoothly and with more generous construction budgets approved by policy makers.

Planning continues for a 12.8-mi line northwest to Sacramento International Airport, but funding and a construction timetable are yet to be decided. As presently operated, the LRT system has three routes:

TABLE 2 Capital Investments: LRT Starter Line and Extensions

Project	km	mi	$Mil Invested[a]	Cum. $Mil	$Mil/ mi	Cum. $Mil/mi
1. Northeast (facilities + 26 LRVs)	29.4	18.3	$175	$175	$9.6	$9.6
2. Add 10 LRVs	—	—	14	189	—	10.3
3. Double-tracking projects	—	—	17	206	—	11.2
4. Mather Field extension	3.4	2.1	33	239	15.7	11.7
5. South Line, Phase 1	10.1	6.3	222	461	35.2	17.3
6. Sunrise extension	4.3	2.7	98	559	36.3	19.0
7. Folsom extension	11.7	7.3	123	682	16.8	18.6
8. Amtrak extension	1.1	0.7	40	722	57.1	19.3
9. Downtown–River District	1.8	1.1	44	766	40.0	19.9
10. South Line, Phase 2	6.9	4.3	270	1,036	62.8	24.2
11. Rehab. 7 UTDC LRVs	—	—	7	1,043	—	24.4
12. DNA (future)	20.6	12.8	799[b]	1,842	62.4	33.2

NOTE: mil = million; cum. = cumulative; UTDC = Urban Transportation Development Corporation.
[a]The author is indebted to D. Nakano, RT Assistant General Manager, Engineering & Construction, for her assistance in confirming the chain of LRT investments (*9*).
[b]Estimate, in 2011 dollars.

- Blue: from Watt/I-80 (northeast) through downtown to Cosumnes River College (south);
- Gold: from the City of Folsom (east) through downtown to the Amtrak station at the northwest edge of the CBD; and
- Green: currently a shuttle route from 13/R Street (south end of the CBD) to Richards Boulevard (an initial stub of the eventual line through the Natomas area to the airport).

HOW MUCH MORE MIGHT FULL DOUBLE-TRACKING HAVE COST?

The starter line as built cost $175 million. This may be compared to the $214 million invested in the first LRT line in Portland, Oregon, opened a year before Sacramento. Differences and similarities between the two projects are presented in Table 3, summarized as follows:

- One-way route length (miles of line): Sacramento (S), 8.3; Portland (P),15.2
- Capital per mile of line: S, $9.6 million; P, $14.1 million
- % double track: S, 40%; P, 93%
- Average station spacing: S, 0.7 mi; P, 0.6 mi
- LRVs per mile of line: S, 1.4; P, 1.7
- Capital invested:
  - Construction, per mile of line: S, $4.21 million; P, $6.84 million;
  - Systems, per mile of line: S, $1.15 million; P, $1.18 million;
  - Vehicles, each: S, $0.92 million; P, $0.96 million;
  - Right-of-way, per mile of line: S, $0.93 million; P, $0.96 million; and
  - Soft costs, % of all other costs: S, 26%, P, 32%.

TABLE 3 Comparison of Initial LRT Lines in Sacramento and Portland

Item	Sacramento	Portland	% Difference
Year opened 1987	1987	1986	—
Miles of line (one way)	18.3	15.2	20
Total capital invested ($million)	$175	$214	–18
Capital per mile of line ($million)	$9.6	$14.1	–32
Differences/Similarities			
Track miles	25.6	29.3	–13
%Double track	40	93	—
Station	26	25	4
Avg. station spacing (mi)	0.7	0.6	—
LRVs	26	26	0
LRVs per mile of line	1.4	1.7	—
Capital by Major Category			
Construction ($million)[a]	$77	$104	–26
Systems ($million)[b]	$21	$18	17
Vehicles ($million)	$24	$25	–4
Right-of-way ($million)	$17	$15	13
Soft costs ($million)[c]	$36	$52	–31
Total ($million)	$175	$214	–18
Capital per Unit by Category ($million)			
Construction (mile of line)	4.21	6.84	–39
Systems (mile of line)	1.15	1.18	–3
Vehicles (each)	0.92	0.96	–4
Right-of-way (mile of line)	0.93	0.99	–6
Soft costs (% of all other)	26	32	—

Note: — = not applicable; avg. = average.
[a] Right-of-way construction, stations and parking, maintenance facilities.
[b] Traction power, signals, communications, fare collection.
[c] Engineering and management, financing, start-up, and testing.

The major cost differences were in construction and soft costs.

Early improvements, Items 2 and 3 in Table 2, added $31 million to the LRT investment. Further improvements to the East Line included as part of the projects in Items 4 and 6 in Table 2 probably added another $15 to $20 million, resulting in an invested total for the enhanced starter line of about $225 million, or $12.0 to $12.5 million per mile of line. Even so, some single track remains, especially the difficult and costly to correct segment crossing the American River. Had Sacramento built the entire line with double track, the per mile capital cost very likely would have been in the range of $15 to $20 million, or a total of at least $275 million. This total, well above the available funding, would have likely discontinued the project. By proceeding, Sacramento was able to put a basic line in service, acquire funds to improve and extend it, and has enjoyed almost 30 years of LRT service it otherwise would not have been able to put in place.

CONCLUSIONS

In common with many transit systems during the Great Recession, the RT suffered a significant drop in the sales tax revenues that fund operations, and the district was forced to reduce both bus and LRT service levels. Only by 2012–2013 did revenues rebound sufficiently to allow some restoration of service hours. The system now operates 76 LRVs and 205 buses. In 2014, the rail system carried 47,500 weekday rides, while buses attracted about 50,000. Annually, LRT rides total 13.5 million, while buses carry 14.3 million, about the same as they did when buses constituted the entire transit system (*10*).

Had LRT implementation been deferred until a theoretically but unnecessarily "perfect" fully double-tracked system could be funded, it is unlikely that there would be any LRT at all in Sacramento today. It is clear that public transit in Sacramento would be much weaker today had the one-time opportunity to build LRT on a cost-effective basis not been seized when it was available and had the appropriate system.

NOTES

1. The city conducted a downtown streetcar study in 1976, but after its conclusion, the mayor and the California Department of Transportation director met and agreed that a longer regional line should be preferred.
2. An unnamed Seattle, Washington, Metro engineer at a project development symposium held in San Diego a few months after the first new trolley line opened there in 1981 (author's recollection).
3. A favorite of current Portland, Oregon, Mayor Charlie Hales.
4. An exception is the bridge over the American River on which LRT occupies an exclusive lane in a preexisting highway bridge over a wetland that also is designated parkland. Double tracking most likely would require a new bridge over this sensitive area.

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Procurement Strategies for LRT and Streetcar Systems

P3 Experiences and Lessons Learned from the Maryland Purple Line Project

GREGORY P. BENZ
WSP–Parsons Brinckerhoff

HENRY KAY
Maryland Transit Administration

The Maryland Transit Administration's (MTA) Purple Line Project is a planned 16-mi east–west light rail transit line between Bethesda and New Carrollton, running just inside the Washington, D.C., area Capital Beltway. The Purple Line has achieved its National Environmental Policy Act of 1969 (NEPA) Record of Decision (ROD) and has been recommended for a FTA Full Funding Grant Agreement (FFGA) in the amount of $900 million. The MTA is advancing the implementation of the Purple Line using a public–private partnership (P3) that involves a contract for a concessionaire having design–build–finance–operate–maintain (DBFOM) responsibilities. The solicitation process schedule has bids due this fall with financial close–notice to proceed expected in late spring or early summer 2016.

The MTA initially developed the project assuming a traditional design–bid–build (DBB) approach. During the preliminary engineering phase of the project, the MTA examined various implementation strategies for the Purple Line. The outcome of the process was a decision to advance the Purple Line as a P3, with certain responsibilities staying with the MTA, particularly right-of-way acquisition, third-party agreements, and ridership–fare revenue risk.

The Purple Line is only the second transit project in the United States being advanced as a P3. This paper describes the process and factors that led to the decision to use a 35-year DBFOM concessionaire-led contract with availability payments (APs). The paper also discusses the solicitation process and contractual mechanisms to achieve the public and owner goals, honor stakeholder commitments, capture innovation and creativity, and maintain a competitive bid environment. The paper highlights the key elements of P3 project implementation; the particular features of the Purple Line P3 approach; the integration with the FTA, NEPA, and New Starts funding processes; the organizational structures and resources required for the procurement and design–build (DB) phases; and lessons learned for other transit projects considering this approach.

The Purple Line Project is a planned 16-mi east–west light rail transit (LRT) line in Maryland between Bethesda and New Carrollton, running just inside the Washington, D.C., area Capital Beltway (Figure 1). The Purple Line will serve five major activity centers just north of Washington, D.C.: Bethesda, Silver Spring, Takoma–Langley Park, College Park–University of Maryland, and New Carrollton. These activity centers are experiencing active development and major projects are planned or underway. The Washington Metropolitan Area Transit Authority's (WMATA) Metrorail system, the nation's second busiest rail transit system, serves four of these major activity centers while three of these centers are served by MARC, Maryland's commuter rail system. Amtrak services along its Northeast Corridor connect at one of the centers. The transit services that connect at these major activity centers are:

- Bethesda: Metrorail Red Line (west line) and a major bus service hub for WMATA Metrobus and Montgomery County's Ride On system.
- Silver Spring: Metrorail Red Line (east line), MARC Brunswick Line, and a major bus interface at Silver Spring Transit Center for Metrobus and Ride On.
- Takoma–Langley Park: A transit center (under construction) for WMATA Metrobus regional system, Ride On bus services, and Prince George's County The Bus services.
- College Park. Metrorail Green and Yellow Lines, MARC Camden Line, and University of Maryland shuttle bus system, as well as Metrobus and The Bus.
- New Carrollton. Metrorail Orange Line terminal, Marc Penn Line, Amtrak Northeast Corridor services, and major bus hub for Metrobus and The Bus.

In addition to these five stations there are another 16 stations serving the residential communities, commercial districts, and institutional establishments between the major activity centers, including three stations serving the University of Maryland with its 37,000 students, 13,000 employees, and visitors. The Purple Line is expected to attract more than 60,000 daily boardings in 2030, more than a third of which are expected to use Metrorail–MARC for some part of their trip, with the Purple Line typically providing the access or egress connection. The project is expected to take 20,000 auto trips off the roads daily. The project is planned to have two maintenance and storage facilities and have a year-of-expenditure estimated capital cost of under $2.4 billion with a start of service by the end 2021.

The Purple Line Project is being advanced by the MTA, which is part of the Maryland Department of Transportation (DOT), as a P3 that involves a contract with a concessionaire having DBFOM responsibilities. Consequently, the funding for the project is a combination from the Maryland Transportation Trust Fund, FTA Section 5309 New Start funds, local government contributions, and the P3 concessionaire financing, which will be repaid over the life of the concessionaire agreement along with payment of the operating and maintenance, and asset replacement costs. The project has secured its ROD completing the NEPA process and is seeking a FFGA from the FTA for the New Starts funds.

The MTA initially developed the project assuming a traditional DBB approach with the MTA operating and maintaining the service and facilities. During the preliminary engineering phase of the project, the MTA examined various implementation strategies for both the Purple Line and its Baltimore Red Line light rail project being developed in parallel. The outcome of the process was a decision to advance the Purple Line as a P3, with certain responsibilities staying with the MTA, particularly right-of-way acquisition, third-party agreements, and ridership–fare revenue risk. The solicitation process schedule has bids due in fall 2015 with financial close–notice to proceed expected in late spring or early summer 2016.

The Purple Line is only the second transit project in the United States being advanced as a P3, with the Denver's regional transportation district Eagle Project being the first. This paper describes the process and factors that led to the decision to use a 35-year DBFOM concessionaire-led contract with APs. The paper also discusses the solicitation process and contractual mechanisms to achieve the public and owner goals, honor stakeholder commitments, capture innovation and creativity, and maintain a competitive bid environment. The paper highlights the key elements of P3 project implementation, the particular features of the Purple Line P3 approach, the integration with the FTA, NEPA, and New Starts funding processes, organizational structures and resources required for the procurement and design–build phases, and lessons learned for other transit projects considering this approach.

In order to capture the innovation and creativity of the integrated DBFOM approach, which includes life-cycle cost responsibilities with consortia bringing international experience and expertise, the contractual requirements for the project were, to the maximum degree possible, performance-based technical provisions, rather than fully developed design drawings and specifications. The MTA wanted to assure certain specific outcomes, such as station aesthetics, landscaping, and fulfillment of certain stakeholder and regulatory commitments, so the contract is more prescriptive for these types of project elements.

PUBLIC–PRIVATE PARTNERSHIP KEY POINTS

In a transportation infrastructure project, P3s are characterized by the following:

- A P3 contract for transportation infrastructure combines the design, construction, and partial or full financing of a project into one umbrella contract.
- Sometimes, a P3 contract also includes long-term operations and maintenance (O&M) in this umbrella contract.
- A P3 contract always places additional risk on the private contractor, which in turn brings value to the public agency and citizens.
- A contractual agreement between the public agency and the private party where:
  - The private party provides financing for funding and operation of a project for public use;
  - The public agency provides some form of performance linked payment to private party in return; and
  - A true partnership shares risk and rewards of the assets and services.

Figure 2 illustrates the range of project delivery methods typically employed for infrastructure projects showing the progression from segmented to integrated procurement and the degree of public versus private financing. The traditional method of delivery transportation infrastructure project in the United Station, especially for transit projects, has been DBB where the owner prepared the design plans and procures (bids) construction and equipment supplier contracts, and coordinates and manages the construction and systems integration and commissioning. DB, where the owner prepares initial project definition plans and then procures a team that is responsible for both the final design and construction, has been become more common over the past decade, increasingly for transit projects. However, the owner would typically retain integration and commissioning responsibilities where project is implemented using several contacts for facilities construction, equipment, and vehicles.

P3 generally is a higher level of integration; some practitioners reserve the term for DBFOM. Others include DBOM, DBF, and DBFM as different forms of partnership with varying degree of risk sharing. DBFOM is one contract for all aspects of the project, from its design to its maintenance and operation.

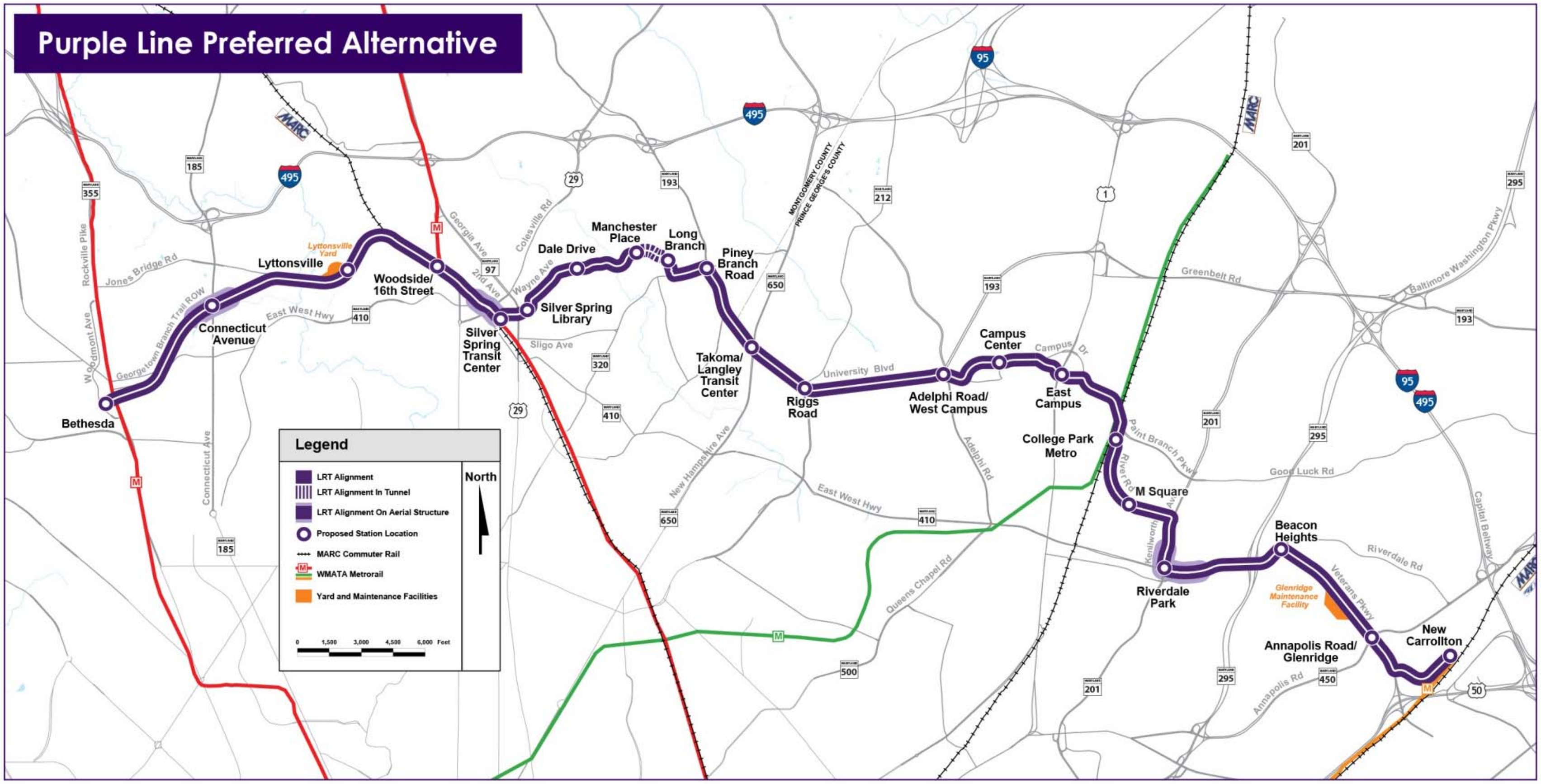

FIGURE 1 Purple Line LRT project.

TRADITIONAL DBB RELATIONSHIP STRUCTURE COMPARED TO DBFOM

As shown in Figure 3, under DBB, the public sponsor (owner) contracts with multiple private contractors for design and construction who have no relationship to or ultimate responsibility for operations and maintenance. The owner arranges all financing typically via tax-exempt debt and is responsible for O&M. Under DBFOM, public sponsor contracts with one private contractor, called the concessionaire, with integrated design, construction, equipment, O&M, who also provide some level of construction phase and long-term financing.

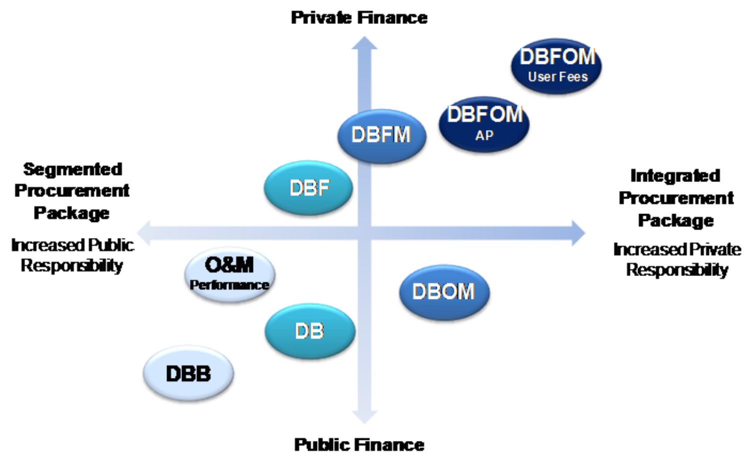

FIGURE 2 Range of project delivery methods.

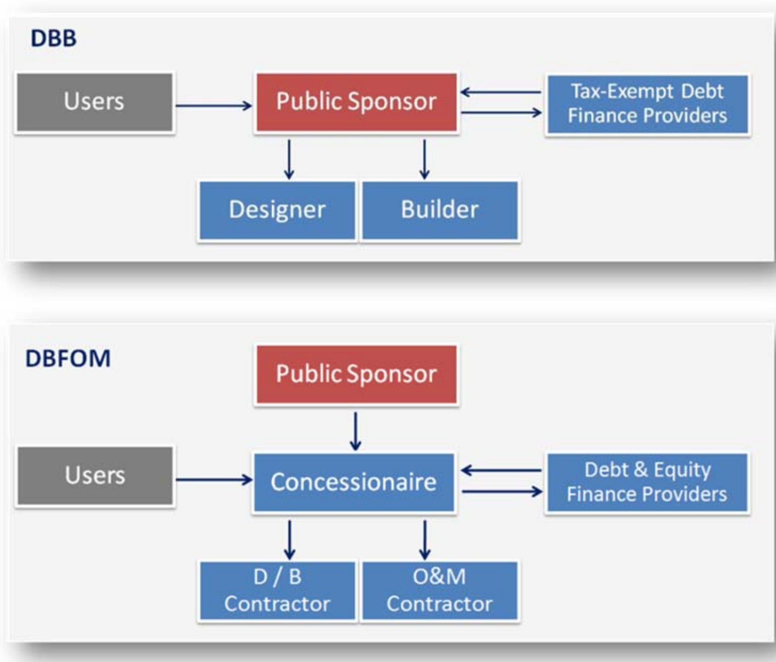

FIGURE 3 Traditional DBB relationship structure compared with DBFOM.

P3 CONCESSION AGREEMENT DEFINED

The P3 concession agreement is a contractual agreement between a public agency and a private sector entity, where

- The private party provides assets and services for use by the general public to prescribed performance-based specifications linked to payment terms;
- Each party shares in risks and rewards in the delivery of assets and services;
- The private party assumes the responsibility (and risks) for DBFOM of the assets; and
- The private party must hand back the project asset to the public agency under the condition required by the contract.

This contractual agreement is generally for a long-term period (i.e., 30 to 99 years). The length of the agreement spread out the relatively high initial procurement costs for both the owner and the concessionaire, covers one or more life cycles for asset replacement, incentivizes the concessionaire to have a long-term interest in the success of project and its operations, and motivates both the owner and concessionaire to truly form a partnership.

Who Is a Concessionaire or P3 Private Partner?

The concessionaire, the private partner in a P3, typically consists of multiple companies combined into a joint venture or similar legal company. These companies invest their cash or loan authority into the project as private equity. The company has a long-term investment in the project and focuses on its long-term performance and not just on an individual component of the project (i.e., designs, construction, operations, maintenance).

Benefits of P3 Concession

While the cost and time to solicit and execute a P3 process can seem daunting compared to more-traditional methods and there is some discomfort in turning over responsibilities that have traditionally been public sector roles to others, a P3 concession provides numerous benefits including:

- Private investors and bond–debt holders add strong oversight to the contractors because they are also at risk if the contractor does not perform (“skin in the game”).
- System integration and performance risk are more effectively transferred to the private sector.
- Design for O&M, as well as construction, are fully optimized.
- There is a single point of contact and accountability throughout the entire contract term.

In the case of rail projects, the construction contractor and vehicle and systems equipment supplier work as an integrated team along with the O&M service providers. To be successful, the concession bidders need to optimize the lowest combination of construction cost, O&M cost, and finance over the life cycle.

What P3s Are Not

Public–private partnerships are not outsourcing, nor are they privatization. With outsourcing, the public entity retains not only all assets but also all risks and rewards, including construction cost and operating revenue, and is responsible for contracting out service. Under privatization, assets are transferred to the private entity for which the public entity receives a payment, and public control is limited to regulation and the terms of the transactions. A P3 is a partnership defined in the contract, under which the public section retains the long-term control for the assets, maintains rights and obligations, and sets service policy; but shares in the risk and rewards with the P3 concessionaire. This comparison is summarized in Table 1.

Often P3 are misconstrued as a transfer of ownership of project assets and a replacement mechanism for traditional financing approaches for all projects. P3 are not primarily about cheaper financing. The governments of the United Kingdom, Canada, France and Australia and many U.S. states have used P3s even though they could fund or finance projects at lower cost due to tax exempt or reduced financing. The value from P3 is created through improved delivery performance, increased risk transfers, and overall lower life-cycle costs achievable by integrating design, construction, and long-term maintenance responsibilities.

P3 Contract Arrangements

The P3 concessionaire sources of funding and revenue come through several mechanisms and depend on the stage of project implementation:

- Milestone payments are lump-sum payments made by the public agency from public funds for a portion of the project cost and typically made during design and construction. There can be some level of progress payments or a payment when the project is available for service or operations.
- Project revenues consist of payments made by users during operations (e.g., tolls, fares).
- APs are periodic payments made by the public agency from public funds during operations (after construction and final acceptance) and based on the "availability" of the project at a certain, well-measured level of performance.

TABLE 1 P3 Compared with Outsourcing and Privatization

	Outsourcing	P3	Privatization
Asset ownership	Public ownership	Usually no irrevocable transfer of assets	Transfer of asset ownership
Public-sector responsibility	Public sector remains responsible for provision of asset and services	Set policy, service levels and rates	Regulation
Level of services	Public responsibility	Mechanism for shared service decisions	Authorities withdraw from service decisions
Risk/reward	No transfer	Shared	All transferred
Mode	Service contract	Partnership	Self-interest

- Ancillary revenues include revenue collected from nonusers (e.g., advertising, development rights, utility rights).

An AP is a performance payment based on the concessionaire meeting established performance requirements. The AP-based P3 transaction is most like a service contract. The public agency owns the guideway, the rail track, etc., from day one and contracts with the concessionaire. Since the AP amount is tied to the concessionaire's performance, the public agency has the right to not pay or make deductions if the concessionaire doesn't perform. The concessionaire uses these payments for their O&M expenses during the operating period and to repay itself for its private investment during the construction period.

MARYLAND PURPLE LINE P3

The MTA and its parent organization, the Maryland DOT, undertook an extensive examination of full range of methods to implement the Purple Line project, including looking at its recent and current DBB, DB, and P3 experience on several major projects, including P3s for a port expansion and for upgrading of highway rest stops. This examination also closely looked at the current P3 transit projects in the United States and Canada that, while limited in number, were instructive in their various structures and provisions. This process led to the decision to use a 35-year DBFOM concessionaire-led contract (a P3) with APs. The key reasons for using a P3 for the Purple Line are:

- Operational factors:
  - Natural stand-alone asset: the MTA operations are centered in the Baltimore region, whereas the Purple Line would be an operational presence in a new location close to the Washington, D.C., area and
  - P3 approach will also increase the likelihood of consistently excellent, highly responsive service.
- Risk transfer efficiencies. P3 will integrate various project elements into a single agreement that clearly outlines the optimal allocation of project risk between the public and private partners.
- Whole life-cycle planning and cost optimization. P3 will provide incentives to make investment decisions that are optimized over the life of the asset.
- Schedule discipline. P3 will provide strong incentives for the Concessionaire to maintain schedule discipline during asset delivery.
- Enhanced opportunities for innovation. P3 will provide the private sector with opportunities and incentives to propose enhancements to the asset design and delivery approach that could benefit long-term operating and maintenance performance.
- Potential financial value. Due to the operational benefits, risk transfer efficiencies, life-cycle planning, scheduling discipline, and innovation opportunities of the P3 approach, there is potential for long-term financial savings relative to a traditional project delivery approach.

With the decision to advance the Purple Line via a P3, the solicitation process used is as follows:

- Request for information–industry forum. By requesting responses from potential bidders and holding a briefing on the project and planned P3 solicitation process, the MTA was able to gauge the industry interest and receive input on structuring the solicitation process and concession agreement. As a result of the this step, the MTA decided have the prequalification of light rail vehicle suppliers occur after shortlisting the concessionaire teams in order to maintain a competitive environment for light rail vehicles during the bid process.
- Request for qualification (RFQ): Six teams responded to the RFQ.
- Short list. Following a review and evaluation, four teams were shortlisted.
- Draft request for proposals (RFP). Confidential one-on-one meetings were held with each of the shortlisted teams to discuss commercial and technical issues and concepts; during this process, draft RFPs were issued and questions and comments solicited to refine the RFP.
- Final RFP. The final RFP was issued to the short-listed teams and many rounds of confidential commercial and technical one-on-one meetings and requests for comments, questions, and clarifications resulted in the issuance of several final RFP addenda.
- Proposed vehicle supplier. Each shortlisted team submitted packages seeking to pre-qualify one or more light rail vehicle suppliers to be part of its team. Suppliers did not have to be exclusive to one team.
- Alternative technical concepts (ATC). Under the process, the teams submitted confidential alternative approaches, methods, or design to the technical provisions or contract documents that would provide an equivalent or superior outcome to what is in the RFP. The owners formally reviewed each submitted ATC relative to an established set of criteria, including capital, O&M, and life-cycle cost savings; compliance with legal, regulatory, and stakeholder commitments, especially the NEPA ROD and third-party agreement; technical acceptability; costs and schedule. If accepted by the owners, the team that submitted the ATC can, but is not required to, include the ATC as part of its bid design and cost estimate. During the confidential one-on-one meetings, potential ATCs can be discussed as their viability and possible acceptability. The ATC process is an essential component to P3 process to achieve the innovation and cost savings and efficiencies of the integrated design–build–equipment supplier–O&M team, through the bid process.

The Purple Line has completed these steps of its P3 solicitation process. The following steps remain:

- Preferred provider. Following submission of the proposals–bids by the short-listed teams, expected in fall 2015, the proposals will go through a technical and financial review and evaluation, including a net present value assessment. A recommended concessionaire team, based on "best-value," will be identified and negotiations toward an agreement with this team will be initiated. This step is expected to be completed in early 2016.
- Commercial close. This step represents the successful negotiation of the commercial terms of the contract between the owner and selected concessionaire team. In the case of the Purple Line, the concluded contract will go before the Maryland Board of Public Works (consisting of the governor, comptroller, and treasurer) for approval. This step is expected to occur in mid-spring 2016.
- Financial close. With an approved contract establishing the commercial teams, including the scope, price, and schedule, the final steps to secure concessionaire short- and long-term financing will be undertaken, and in the case of the Purple Line, the owner will be securing

its FTA full funding grant agreement for federal New Starts funding. This milestone is expected to occur in late-spring 2016.

- Design–construction. The notice to proceed issued immediately upon financial close will initiate design and construction.
- Commissioning. Commissioning is expected to occur approximately 4 years from the start of design and construction.
- Operations. Expected to occur approximately 1 year from commissioning.

MTA Is Retaining Primary Responsibility for Certain Elements

While a majority of the design and construction will be assigned to the concessionaire, the MTA is retaining exclusive or at least primary responsibility for certain project elements since it is in a more appropriate position to accomplish the work or to hold the risk:

- Public information, communications, and community and stakeholder involvement;
- General terms of third-party agreements;
- Right-of-way acquisition, including committing to the concessionaire the availability dates of each specific property or easement;
- Fare policy, farebox revenue, and ridership risks; and
- Transit-oriented development activities not included in project (or P3).

How Key Objectives Are Addressed in P3

One of the concerns heard from stakeholders relative to a P3 was that public policy goals and commitments made to communities and other parties, especially those soft commitments that are outside of formal agreements and environmental mitigation obligations, would not be honored by "turning the project over to a private contractor." The MTA invested a significant effort in developing the RFP and contractual mechanisms to achieve the public and owner goals and honor stakeholder commitments, while still capturing innovation and creativity and maintaining a competitive bid environment that are among the primary advantages of using the P3 approach. Areas that received particular attention developing the RFP and contract documents were

- Service quality and reliability;
- Station planning–aesthetics; and
- Community–third-party agreement–ROD commitments.

A discussion of each of these contractual mechanisms is provided below.

Service Quality and Reliability

The P3 agreement translates service quality and reliability policies into contractual requirements, including headways, loading standards, acceptable delays, and other such standards. The contractual enforcement mechanism is the AP, where deductions from the maximum potential payment result from "nonconformance" events such as missed trips, headway nonachievement, cleanliness issues and equipment availability. A factor system is used to establish the monetary deductions from the periodic APs as well as uses an accumulation of factors to enable the owner to take additional actions if nonconformance is chronic and corrections or improvements are not addressed. Table 2 illustrates some of the factors that determine the deductions for nonconformance events relative to the LRV availability.

Station Site Planning—Aesthetics

An essential characteristic of the db portion of a P3 implementation approach is to provide performance provision for the design–construction of the project facilities, systems and equipment and vehicles. The focus is typically on outcome rather than the means and methods of construction and even the details of the design. The Purple Line is being "inserted" into the well-developed set of communities along the project corridor. During the planning and early development phases of the project, the "light touch" of the facilities, especially the transit stations, into the communities was an essential feature of the project, including the aesthetics of stations. So while the majority of the facilities and systems are largely addressed in the RFP and contract documents through performance-based technical provisions, the aesthetic profile of the essential elements of the transit stations and immediate site configurations are prescribed in the contract drawings and technical provisions. While not dictating the means and methods of constructions, the dimensions of and material types of various station elements are prescribed as a means of ensuring the station will be constructed as committed to the stakeholders.

Community–Third-Party Agreement–ROD Commitments

The MTA has made a number of legal and "soft" or "moral" commitments to the nature and location of certain facilities, the mitigation impacts during construction and during operations, and the performance of the Purple Line project. Many of these commitments are contained in the numerous third party agreements and in the NEPA ROD based on the project's final environmental impact statement. In additional to these legal obligations, the MTA has made additional commitments—"moral obligations"—to community groups and organizations. These commitments are implemented through the technical provisions and the contract agreement. The concessionaire's–MTA's responsibilities in carrying out the various commitments are defined in the contract as are the interfaces. Construction phase incentive–penalty clauses in the P3 contract are designed to enforce some specific provisions of the P3 contract.

TABLE 2 Illustrative Availability Payment Nonconformance Deduction Factors

Vehicle Availability Nonconformance Event	Nonconformance Factor
Unsequenced train, peak (vehicle bunching)	0.80
Late train, off peak (more than 5 min)	0.80
Late train, off peak (more than 7.5 min)	1.10
Late train, off peak (more than 10 min)	1.30
Short train	1.30
Early departure, off peak (15 s)	1.30
Incomplete trip (never reaches scheduled terminal)	2.50
Missed trip (never departs scheduled terminal)	2.50

Particular Features of the Purple Line P3 Approach

While the Purple Line P3 implementation approach has many features in common with recent comparable P3s, there are number unique or new elements. Some examples are discussed below.

Run-Time Adjustment

One of the intents of the P3 approach is to incentivize the concessionaire to proactively manage the operations of the Purple Line service to meet the service quantity and quality provisions, but also to minimize the capital and operating and maintenance costs in the bid price. As the Purple Line will operate along or in numerous roadways, changes in the levels of traffic congestion caused by external factors and uncertainties of traffic signal timings and various priority/pre-emption treatments controlled by local jurisdictions introduce risks to bidding based on a given run time. The Purple Line RFP provides sets of traffic signal and traffic congestion run-time delays for the system at different times of the day on which all the teams are to base their bids. Just prior to the start of revenue service, the contract includes a testing regime to establish the actual traffic signal and congestion run-time delays and provides a change order mechanism for making adjustments, including adding to the light rail vehicle fleet, if the delays are sufficiently longer than initially established to merit such a remedy. The intent is to reduce the amount of light rail vehicle run-time risk contingency that bidders would include in their bids.

Integration with the FTA, NEPA, and New Starts Funding Processes

The MTA made a concerted effort to receive the Purple Line NEPA ROD and an associated National Parks Service ROD prior to the issuance of the P3 RFP. The RODs and their commitments are part of the P3 contract. While the MTA is ultimately responsible for the commitments in the RODs, the contract assigns the implementation of most of the commitments to the concessionaire. The MTA will implement certain commitments such as some out-of-corridor mitigation that may not be fully defined until after the bids. This approach removes a substantial amount of bid uncertainty and risk relative to the environmental issues and permits.

The Purple Line has been recommended for a $900-million FTA FFGA under the New Starts program. The Purple Line received permission to enter preliminary engineering on October 7, 2011, before changes to the New Starts project development process were enacted under the Moving Ahead for Progress in the 21st Century Act (MAP-21). The project was subsequently grandfathered into project development under MAP-21 and the MTA received approval for entry into engineering on August 28, 2014. The project is applying for its FFGA which is scheduled to be received by financial close. The FTA at a policy level is supportive of the concept of a P3 as an innovative alternative financing–project implementation mechanism. With the Purple Line being only the second P3 under the New Starts program, FTA's procedures and practices have not yet been adapted. The principal issues are the timing and level of project definition detail expected at the start of the application process. Typically, a FFGA can take 6 months or more to process and received approval, including FTA staff and policy review and mandated time periods for U.S. Office of Management and Budget and Congressional reviews. The FFGA application includes dozens of management plans, project definition, cost and risk assessments, and related documents with firm quantitative definitions of the scope, schedule and especially capital cost, including contingencies. Under a typically DBB procurement process, the project would be at 100% design and the bid process well underway by the time the project would be applying for the FFGA so providing this specificity is not normally an issue. Under a P3, the project scope, while well established from an overall project definition standpoint (length, number of stations), the project at the start of the FFGA application has only been designed to a 20% to 30% level which determines in turn the level of certainty around the schedule, capital cost, and risk assessment. The length of time between the receipt of bids and financial close is roughly 6 months, however the first 2 months is required for bid evaluation. Once a bidder is selected for negotiations, the MTA will have a firmer idea of the cost and schedule as well as quantities for scope items, especially for light rail vehicles, traction power substations and related power system elements, special track work, and maintenance and storage facilities layouts and equipment, and so on. In addition, the bidder's accepted ATCs included in the bid will now be known. So while the information required for the FFGA application is now firmer for processing, the actual final quantities and cost information will not be established until the negotiation are complete and the agreement is ready for commercial close, which is expected to be only be a little more than three months before the needed FFGA approval at financial close. The timing of the financial close relative to bid submission is set by how long bidders can be expected to hold bid prices, interest rates, financial ratings, and other time-sensitive financial items. The MTA continues to work with FTA to process the FFGA application in advance of commercial close based on the best available information representing the upper range of the expected capital cost bids. The idea is that if FTA establishes the financial acceptability of the application at a number higher than the final application cost, then once the final number is established, it is merely a matter of updating the application with numbers that are comparable or lower, and not having to reinitiate or take steps backwards in the process by resubmitting the project with higher costs.

The MTA has also initiated the process to make available to the concessionaire a U.S. DOT TIFIA loan, which provides a lower interest rate, as part of the project financing. The TIFIA process also requires project scope, schedule and budget information but not at the level of specificity required for the FFGA, so integrating the TIFIA process and schedule with the P3 solicitation schedule and New Starts has been relatively straightforward.

Lessons Learned for Other Transit Projects Considering This Approach

New Starts Process

As more U.S. transit projects employ P3 or similar alternative procurement approaches in combination with the New Starts program, FTA policies and procedures for processing and approving a FFGA will likely adapt to recognize the timing, process, and information availability inherent in P3 or similar approaches.

Organizational Structures and Resources Required

While a major transit agency typically has the resources and experience necessary to implement a traditional procurement approach for capital and O&M contracts, a P3 approach requires additional procurement, legal, financial, transactional, and insurance expertise with specific knowledge and expertise in P3s to guide the process through the policy, technical and industry engagement steps. In some cases, changes to state or local laws or enabling legislation may be required. The engagement with the P3 industry (concessionaire lead, designers, constructors, equipment–vehicle suppliers, operators, maintainers, and financial and legal entities) is critical prior to and during the solicitations process to get a good response to the solicitation and get competitive and responsive proposals–bids that meet the owner's goals for the project.

The owner's technical staff that is responsible for the service planning and facilities–systems design need to be able to develop technical provisions based on performance measures during construction and O&M rather than the full design plans found in a DBB. For agencies that have been employing the DB approach or developing service operations or maintenance contracts, the approach is similar. The technical staff need to be comfortable with engaging in the technical and commercial one-on-one meetings and the ATC process during the solicitation process, which is different from the usual "disengagement" that occurs during typical procurement process. Once the agreement is executed, the contract management and quality assurance during design and construction is a "lighter touch," where design reviews are to assure compliance with the contract technical provisions and the owner provide quality assurance oversight rather than more traditional construction management. This can take some adjustment in culture for staff and consultants accustomed to the more traditional "hands-on" roles. During the O&M phase there will be some similarities to contracted service and maintenance agreements; but contract management will require additional management, financial and legal expertise to handle the numerous performance measures, quality monitoring and financial adjustments associated with the AP process.

Third Parties

Every project will have agreements with a number of third parties, including local jurisdictions, utilities, other governmental and quasi-governmental organizations, to address right-of-way—entry and easements, relocations, maintenance of traffic, traffic operations/signal operations, and reconstruction and/or replacement of their bridges, roadways, and other structure and facilities and their post-constructions ownership and maintenance—among many other issues. Getting theses third parties acclimated to a P3 contract approach, especially to design and construction phase oversight and acceptance, and integrating the third party-specific design standards and review–acceptance requirements, especially timing, proved to be a major challenge in the development of the RFP. Uncertainties around timing of reviews and acceptance by the third parties and access to information on existing conditions and as builts, especially for the utilities, was seen as a major risk by the bidders as well as the owner. This prompted refinement of the design and technical provisions to minimize utility disturbance and relocations wherever possible, and putting as much of the utility design and relocation work as possible in the P3 contract under the control of the concessionaire.

Public Perception

The Purple Line Project is being placed into a well developed corridor with many communities with long history of active engagement with public and private development projects. The project has had a very proactive engagement with the communities and stakeholders and has actively worked with these groups on station and other facility locations and design treatment, mitigation, and enhancement components of the project. The initial concerns regarding a P3 were that the project was being turned over to the private sector and that the MTA would not be honoring its commitments and that the private sector cost cutting would diminish the quality of design, constructions, and service provided. As discussed earlier, the MTA has embedded into the RFP and contract the legal, regulatory and soft commitments made to the communities and stakeholders. The MTA is still ultimately the owner of the project and responsible for it safety, security, quality and performance. The MTA invested a significant amount of effort in providing information and reaching out on the P3 process and how community commitments will be addressed, as well as making the RFP and other materials publically available to the extent possible within the boundaries of the solicitation process.

SUMMARY

The MTA chose to use a P3 to implement and operate the Purple Line Project based on an assessment of this approach's ability to achieve the project's goals and its benefits, costs, and risks relative to other procurement processes. With that decision, the approach to the subsequent project development and procurement steps required a shift in thinking and resources needed to advance the P3 process. It also required that same adjustment in dealing with federal and local stakeholders. Therefore it was incumbent on the MTA to invest in informing and engaging with these stakeholders to make sure they understood and were comfortable with the process.

For further information on community and stakeholder outreach activities, access to technical reports and drawings, and to stay current as the Purple Line Project move towards implementation, please visit the project website at www.purplelinemd.com.

Insertion of Streetcars and LRT in Urban Street Environments

Downtown Distribution for Light Rail Transit
Past, Present, and Future

HERBERT S. LEVINSON
Transportation Consultant

JOHN G. ALLEN
Transportation Consultant

Downtown distribution has been a major concern for transit systems since electric traction began in the late 19th century. Congestion between transit vehicles and street traffic predates the automobile. To address these operating issues, several large cities placed streetcars underground, and a few provided new grade-separated entry into the city center. The modern light rail era has seen both street running and off-street access.

This paper discusses downtown access for modern light rail transit (LRT) lines. It sets forth the trade-offs between operating speed and reliability, costs, and environmental and other effects. It briefly reviews the past experience of downtown distribution for light rail lines and electric interurban railways with light rail characteristics before discussing present-day developments. Most modern light rail lines use street access, saving capital cost at the expense of lower speed. Two of the four newer systems with downtown subways use previously existing tunnels.

For transit authorities, the choice between downtown street running and subways involves trade-offs between capital cost and operating considerations, particularly speed and interactions between trains and traffic. For customers, the trade-offs are mainly between the speed and ease of physical access to downtown stations and running time through the downtown area. Finally, for cities, the trade-offs involve the quality of downtown rights-of-way versus the total alignment that a given investment level can provide.

INTRODUCTION

Light rail systems serve downtown areas operating on city streets or other, separated rights-of-way. Traffic congestion in and near downtown has been a major concern for traction companies and transit authorities since the late 19th century. For much of the 20th century, street running was seen as obsolete, undesirable, and incompatible with modern transit operations and traffic engineering. As a result, all cities retaining what are now light rail systems eventually built downtown subways for these services.

Modern LRT in North America began in 1978 when Edmonton, Alberta, Canada, opened its line (which includes a downtown subway). A new paradigm of modern LRT with street running in the central business district (CBD) emerged in 1981 with the opening of the Calgary, Alberta, Canada, and San Diego, California, systems. Since then, CBD street running has become an important part of the overall light rail design package. Important new systems in

Portland, Oregon, Denver, Colorado, and Dallas, Texas, also operate on downtown streets. At the same time, a few modern properties, including Los Angeles, California, use downtown subways.

This paper discusses the pros and cons of different approaches, based on system characteristics and downtown employment. Although overbuilding should be avoided, the high ridership volumes at some properties suggest that street running imposes costs of its own in terms of running time, as well as offering considerable capital cost savings.

Downtown distribution is a vitally important issue for any light rail system. In 1997, John Schumann had this to say about downtown areas and transit:

> Every city still has a downtown. It is, or should be, the cultural heart of the metropolis and the logical place for highly specialized activities occurring in just one location within an entire urban region. With its concentration of jobs, it is transit's best market. Symbiotically, good transit makes downtown work better (*1*, p. 209).

The two main downtown distribution options are subways and street running. Street operation can be further divided into these sub-groups:

- Operation in mixed traffic, sharing traffic lanes with motor vehicles (e.g., Toronto, Ontario, Canada);
- Transit-only malls, sharing with buses (e.g., Calgary); and
- Light rail only (e.g., Sacramento, California).

These subgroups are differentiated from each other in terms of how streets are managed, but there are few physical differences between them. Therefore, street operation is discussed here as a single option.

The other form of downtown distribution is on private rights-of-way. Almost always this means a subway, usually dug cut-and-cover beneath one or more streets. Cleveland, Ohio, and Charlotte, North Carolina, however, use former railroad rights-of-way.

Table 1 provides an overview of the different outcomes with regard to vintage of light rail system and forms of downtown access. Three columns show abandoned, historically established and newer light rail properties. The rows indicate downtown right-of-way types: city streets, subways built along with light rail, subways built considerably later, and other alignments.

Table 2 provides additional data about individual systems, indicating annual and average weekday ridership, system length, downtown employment (where available) for the 1990–2000 period (when many cities had opened, were building, or planning light rail), high or low platforms, and form of downtown access.

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TABLE 1 Downtown Distribution on Various Light Rail Properties

Running Way Type	Abandoned Systems	Older Light Rail Systems	Newer Light Rail Systems
City streets	• Milwaukee, Wis. (West Side Rapid Transit)	• New Orleans, La. (streetcar system) • Toronto (streetcar system)	• Baltimore, Md. • Buffalo, N.Y. • Calgary, Alberta, Canada • Dallas, Tex. • Denver, Colo. • Houston, Tex. • Jersey City, N.J. • Minneapolis–St. Paul, Minn. • Norfolk, Va. • Phoenix, Ariz. • Portland, Ore. • Sacramento, Calif. • Salt Lake City, Utah • San Diego, Calif. • San Jose, Calif.
Subway (built by 1930s)	• Los Angles, Calif. (Pacific Electric) • Rochester, N.Y. • St. Louis, Mo. (Illinois terminal)	• Boston, Mass. • Newark, N.J. • Philadelphia, Pa. (A)	
Subway (built after 1930s)		• Pittsburgh, Pa. • San Francisco, Calif.	• Edmonton, Alberta, Canada • Los Angeles, Calif. (B) • St. Louis, Mo. (C) • Seattle, Wash. (C)
Other rights-of-way	• Oakland, Calif. (Key System) (D)	• Cleveland, Ohio (E)	• Charlotte, N.C. (F)

NOTE: A = subway–surface lines only (Philadelphia's Girard Avenue, Media, and Sharon Hill lines not included because they do not serve the downtown area); B = Blue and Expo Lines only; C = subway tunnel predates light rail system and was converted for light rail use; D = tracks built on lower level of double-deck highway bridge across San Francisco Bay; E = former Shaker Heights line has one station serving downtown core via railroad right-of-way; subsequent distributor line to adjacent entertainment district uses railroad and other reserved alignments, partly running at grade; F = former railroad alignment running at grade through central business district, parts of which have been upgraded to resemble a transit mall.

TABLE 2 Light Rail System Ridership, Length, Downtown Employment, and Downtown Access

City	Unlinked trips (thousands), 2014 (A)	Average Weekday Trips (thousands), 2014 (A)	System Length 2014–2015 [miles (B)]	Downtown Employment (thousands), 1990–2000 (C)	Platforms	Downtown Alignment	Notes
Older Systems							
Boston, Mass.	69,378.4	223.3	26.0	270	Low	Subway	(D)
Cleveland, Ohio	2,778.6	NA	15.3	100	Low	(E)	
New Orleans, La.	7,457.2	23.0	22.3	NA	Low	(F)	Line-haul streetcar operation.
Newark, N.J.	5,256.7	18.5	6.2	NA	Low	(G)	
Philadelphia, Pa.	31,481.9	111.9	68.4	265	Low	Subway	Also includes nondowntown lines.
Pittsburgh, Pa.	8,166.1	27.7	26.2	110	(H)	Subway	
San Francisco, Calif.	56,712.9	128.5	35.7	320	(I)	(J)	Includes vintage streetcar service.
Toronto, Ontario, Canada	91,588.2	291.8	51	400 (K)	Low	Street running	Line-haul streetcar operation.
Newer Systems							
Baltimore, Md.	8,092.3	27.1	33.0	98	Low	Street running	
Buffalo, N.Y.	5,356.7	18.5	6.4	43	(L)	Street running	Runs in subway outside downtown.
Calgary, Alberta, Canada	86,648.1	236.7	36.5	NA	High	Street	
Charlotte, N.C.	5,130.4	15.8	9.6	53	Low	(M)	
Dallas, Tex.	29,884.2	101.8	77.6	112	Low	Street	(N)
Denver, Colo.	26,362.9	86.3	47	121	Low	(O)	
Edmonton, Alberta, Canada	34,751.4	109.7	13	NA	High	Subway	
Houston, Tex.	13,300.7	45.3	12.8	161	Low	Street running	
Jersey City, N.J.	16,691.6	54.4	17.0	NA	Low	Street running	Serves Exchange Place area.
Los Angeles, Calif.	63,890.0	200.8	70.3	215	High	(P)	
Minneapolis and St. Paul, Minn.	16,000.1	62.5	21.8	105 (data for Minneapolis)	Low	(Q)	
Norfolk, Va.	1,695.9	5.8	7.4	NA	Low	Street running	

Continued on next page.

TABLE 2 (*continued*) Light Rail System Ridership, Length, Downtown Employment, and Downtown Access

City	Unlinked trips (thousands), 2014 (A)	Average Weekday Trips (thousands), 2014 (A)	System Length 2014–2015 [miles (B)]	Downtown Employment (thousands), 1990–2000 (C)	Platforms	Downtown Alignment	Notes
Newer Systems							
Phoenix, Ariz.	14,263.7	44.8	19.6	36	Low	Street	
Portland, Ore.	38,164.6	113.9	66.7	104	Low	Street running	Portland Streetcar not included.
St. Louis, Mo.	17,182.1	49.9	46.0	85	High	Subway	Previously existing rail freight tunnel converted to light rail.
Sacramento, Calif.	13,399.0	45.2	38.6	60	Low	Street running	
San Diego, Calif.	39,731.9	119.8	53.5	86	Low	(R)	Includes vintage streetcar service.
Salt Lake City, Utah	19,868.7	68.5	44.8	59	Low	Street	
San Jose, Calif.	11,345.6	35.2	42.2	31	Low	Street running	
Seattle and Tacoma, Wash. (*S*)	11,915.9	35.2	17.3	110 (Seattle)	Low		Light rail tracks laid in previously built downtown Seattle bus tunnel.

NOTE: NA = not available; A = All ridership data from APTA (*2*) except as noted. B = Data from Wikipedia (*3*). C = Data from Levinson and Kalluri (*4*) except as noted. D = Data include the Mattapan High-Speed Line, a separate light rail line operated with vintage equipment that does not serve downtown. E = Grade-separated and street-level former railroad alignments, plus newly built overpass. F = Street medians and street running.G = Subway, plus some newer street running. H = High platforms in subway and selected stations elsewhere; otherwise low platform. I = High platforms in subways and a few other locations; low platforms elsewhere. J = Most downtown distribution via subway with shorter portion on fringe of downtown area on streets; vintage streetcars operate on streets exclusively. K = Data from City of Toronto Employment Survey. L = Low platforms on downtown streets, high platforms in subway beyond downtown. M = Former at-grade railroad alignment, rebuilt with pedestrian walkways alongside. N = One line runs in a subway outside downtown.O = Street running in downtown core, supplemented by alternative route along railroad alignment and other private rights-of-way on edge of downtown. P = Subway for Blue and Expo Lines, which serve downtown core; extension of subway planned to Los Angeles Union Station just beyond downtown area to bring Gold Line light rail into downtown. Green Line does not serve downtown. Q = Street running in both downtowns.R = Street running in downtown core, supplemented by alternative route along railroad alignment on edge of downtown. S = Combined total for physically separate Seattle and Tacoma operations. T = Subway in downtown Seattle; street running in downtown Tacoma.

DOWNTOWN ACCESS: STREET OR SUBWAY?

Aside from the large streetcar system in Toronto and the historic New Orleans, Louisiana, streetcars, other long-established North American systems surviving beyond the 1960s opened downtown subways between 1897 and 1985, as downtown street congestion was long an issue in these cities. Furthermore, for much of the 20th century, street running was seen as obsolete, undesirable, and incompatible with modern standards for transit systems and traffic engineering alike. As a result, these cities viewed downtown subways—despite their cost—as part of broader modernization plans to bring their operations up to modern light rail standards.

But just before the last of these light rail subways opened, a new paradigm of modern light rail transit with street running in the CBD emerged with the 1981 opening of the Calgary and San Diego systems. Since then, street running has become an important part of the overall design package for new-start light rail properties in cities well below the threshold for rapid transit.

Before the light rail renaissance that started in the 1980s, no intermediate forms of treatment existed between street running in mixed traffic and fully separated, but capital-intensive, subways. Various systems used safety islands at downtown stops, but there was no further separation from vehicular traffic. Some systems, such as Pittsburgh, adopted a pay-leave system of fare collection to expedite outbound travel from downtown, but proof-of-payment, now used on most LRT properties, was then unheard of in North America (*5*).

Since 1981, many new LRT operations have used street running in downtown areas, but with an important difference. Traditional streetcars operated in mixed traffic, whereas most modern LRT systems with street running use reserved lanes or transit-only malls.

The choice between street running and subways for downtown distribution involves cost–benefit trade-offs. The different types of downtown distribution are discussed by historical category (abandoned, older or newer systems) and right-of-way type (street or subway).

ABANDONED SYSTEMS

Most abandoned street railway properties ran exclusively, or almost exclusively, in city streets, and served downtown through street running in mixed traffic. These conventional systems are not considered further here. Sometimes, more sophisticated operations that would now be considered light rail, such as the Illinois Terminal's (IT's) approach to downtown St. Louis, Missouri, looked for alternatives to the downtown access problem (*6–8*).

Until the opening of the San Diego and Calgary systems in 1981, interurbans and transit operators made sustained efforts to move trains off city streets and onto subways and other private rights-of-way if they could afford to do so. Several now-abandoned systems built terminals as part of elaborate downtown access projects. (A single downtown station is still found in Cleveland, but this approach has not been used for newer LRT systems, perhaps because it reduces convenience by requiring downtown customers to walk or find other means of reaching the terminal.)

Some interurbans that used streets to reach downtown built substantial off-street downtown terminals, such as in Indianapolis, Indiana, the Chicago, North Shore and Milwaukee terminal in Milwaukee, Wisconsin, and Pacific Electric's 6th and Main terminal in Los Angeles.

These may be seen as precursors of modern transit centers such as the one in uptown Charlotte (now served by most Charlotte Transit System bus routes and the Blue Line light rail).

The most interesting terminal projects, however, combined a downtown station with major right-of-way improvements. In Los Angeles, Pacific Electric (PE), the country's largest interurban system, had an extensive street railway network west of downtown. To better serve this growing business, PE opened a subway in 1925 beneath Bunker Hill, then a residential neighborhood just west of downtown, ending at a new terminal serving the city's traditional commercial district. The subway and all lines serving it were abandoned in 1955 (*9*). Since then, Bunker Hill has become greatly built up and is the core of today's downtown area. As a result, the historic terminal is less centrally located now than it was in the early 20th century.

In 1927 and 1930, Milwaukee's traction company opened segments of a new grade-separated alignment to the west and southwest of downtown, known as the Rapid Transit. Just before reaching downtown, the private right-of-way ended, and trains ran several blocks in city streets to reach the company's downtown terminal. Construction began on a downtown subway to link the Rapid Transit with the terminal, but the Great Depression brought an end to those efforts (*10*). The Rapid Transit was abandoned in 1951, and the innermost segment of the exclusive alignment is now used for Interstate 94.

Another downtown terminal combined with extensive improvements was in St. Louis. Illinois Traction, subsequently IT, built a bridge across the Mississippi River in 1910 to bring its local streetcars and longer-distance interurbans into a downtown St. Louis terminal. But the slow street running and the cramped terminal proved inadequate. Furthermore, the city planned to widen the street where the terminal was situated, forcing IT to relocate. Accordingly, the company built a new elevated alignment in 1931 (eliminating all but a short section of street running). In 1933 IT opened a new downtown terminal for passengers and freight, reached via a short subway (*11*). Light rail service was discontinued in 1958, but during the short life of these improvements, they made service substantially faster.

Until 1939, the Key System, an Oakland, California-based street railway, operated ferries to take its passengers to downtown San Francisco. In that year, a two-track electric rail line opened on the lower level of the San Francisco–Oakland Bay Bridge, serving the then-new Transbay Terminal in San Francisco, Key System, interurban Sacramento Northern, and Southern Pacific's electrified commuter trains originally used the bridge tracks, although the latter two ceased service by 1941 (*12*). Key System trains continued to operate on the bridge until 1958.

Finally, in Rochester, New York, an abandoned section of the Erie Canal was reused for light rail starting in 1927 (the line also accommodated interurban trains serving Rochester). Trains ran through a mile-long downtown subway (with a new downtown street built above the canal bed), making Rochester the smallest city in North America with a subway. Three downtown Rochester stations provided good distribution. Service ended in 1956, and part of the right-of-way is now used for a freeway (*13*).

SURVIVING SYSTEMS

Most transit properties still operating streetcars by the late 1960s had by that time, or subsequently, opened downtown subways. Two continue to operate on downtown streets.

Street Running

City streetcar operations in Toronto, Ontario, Canada, and New Orleans, Louisiana, have survived to this day from the 19th century. Toronto's streetcars operate in mixed traffic. The New Orleans lines run largely in medians (locally known as neutral ground) along Canal and St. Charles Streets, although some street running is also involved. These properties show that under certain circumstances, streetcars can work in line-haul applications. Nevertheless, both systems differ significantly from modern LRT systems with more varied rights-of-way.

Older Subways

Larger cities found it increasingly difficult to provide reliable streetcar service in downtown traffic, particularly along narrow streets. Although several cities, including Chicago, Illinois, planned subways for streetcars, only three (four including the now-abandoned Rochester line) built subways by the 1930s.

The first was Boston, Massachusetts, where narrow, irregularly arranged streets intensified downtown congestion. Construction began on a subway for streetcars beneath Tremont Street in 1895. In 1897 Boston became the first U.S. city to have a subway, seven years before New York's first underground line (for rapid transit). An extension to the nearby Back Bay district under Boylston Street opened in 1914, with a short supplementary extension opening under Huntington Avenue in 1941. Five routes, collectively known as the Green Line, continue to use the subway today (*14*).

In 1905, Philadelphia, Pennsylvania, opened a subway between City Hall and the Schuylkill River for certain routes serving West Philadelphia's neighborhoods. (This paralleled a rapid-transit subway between the Delaware River, City Hall, and the Schuylkill River.) The initial subway was followed in 1955 by an extension crossing the Schuylkill into West Philadelphia, where routes disperse near the University of Pennsylvania (*15*). Five of these subway-surface routes operate today. Street running in mixed traffic beyond the subway affects their operating reliability, although the subway's advantage in bypassing closer-in traffic congestion continues to make these lines attractive to riders.

Historically, Newark, New Jersey, had a busier downtown area than has been the case since the 1960s. By the 1920s, traffic congestion was impeding the flow of streetcars through downtown. Accordingly, the city built a subway (and a trunk line in an abandoned canal bed), with construction starting in 1929 and the line opening in 1935 (*16*). Between the 1950s and the 1990s the line was little changed, but new cars were acquired and the line was extensively rehabilitated at the start of the 21st century, and a short outer extension was built.

In 2006, a mile-long extension opened between the downtown terminal at Newark Penn Station (used by Amtrak and commuter trains) and Newark Broad Street Station (used by another commuter rail line). The extension, which used street running for the most part, took advantage of a long-disused flyover junction in the subway to a former traction terminal (*17*, pp. 121–123). The trunk line service and the Broad Street shuttle are operated as separate services, both of which stub-end into Newark Penn Station.

Newer Subways for Older Systems

Two older light rail properties opened downtown subways in the 1980s. San Francisco built tunnels through hills along two main streetcar routes during the 1920s. By the 1960s, San Francisco's handful of surviving lines converged on Market Street downtown, a major commercial thoroughfare running along the intersection of two distinct street grids. As part of the regionwide Bay Area Rapid Transit system, a two-level subway was built under Market Street, with the LRT element opening in 1980. The upper level accommodates light rail, and rapid transit trains use the lower level (*18*). By 1982, all routes had been shifted to the subway, although the Market Street tracks are now used for a tourist-oriented heritage streetcar service.

Pittsburgh, Pennsylvania, almost replaced its aging and undermaintained South Hills trolley lines with a new automated-guideway line, but concerns about capital cost and the wintertime reliability of rubber-tired technology led to a 1976 decision to renew the rail lines, which ran on city streets through Pittsburgh's congested downtown (*19*). A new subway replaced street running in 1985.

Other Alignments

Until it was replaced with a short extension of an older subway in 2004, Boston's Green Line used a short section of elevated railway between Haymarket, North Station (a major commuter rail terminal) and Science Park, where the line runs on a historic viaduct to Lechmere, just outside the central area. (An extension beyond Lechmere to Somerville is in advanced planning.)

In Cleveland, Ohio, the Blue and Green Lines (formerly the Shaker Heights Rapid Transit) switched in 1930 from a slow route involving trackage rights on the local streetcar system on busy Euclid Avenue to a faster route alongside a railroad alignment to reach the Terminal Tower complex (located toward one end of downtown Cleveland). Although this change accelerated light rail operations considerably, Terminal Tower was located toward the west end of the downtown core, resulting in less direct travel for many commuters as the Shaker Heights trains approach downtown from the east (*20*). The ridership effects of this change cannot be separated from the impacts of the Great Depression, but Cleveland's experience suggests that faster service to a single downtown point is not the same as improved service to the entire downtown area. Since 1955, the innermost portion of the light rail line has been shared (uniquely in North America) with a rapid-transit line.

Cleveland's downtown distribution problem was never fully resolved, although in 1996 the light rail line was extended 2.2 miles along former railroad and other private rights-of-way to serve parts of Cleveland's entertainment district. The 2008 opening of the Health Line bus rapid transit along the Euclid Avenue corridor has helped improve transit distribution along Cleveland's busiest downtown street. (The Health Line, unlike predecessor services, features transit priority.)

NEW SYSTEMS

The modern light rail renaissance began with the 1978 opening of a line in Edmonton, using a downtown subway. Since the 1981 opening of LRT systems in Calgary and San Diego, most new systems have used street running (usually in the form of reserved lanes and transit-only malls).

Street Running

Cost-conscious planners, seeking to make light rail affordable in metropolitan areas below the population, downtown employment or density thresholds for rapid transit, have generally selected at-grade alignments in city streets for downtown distribution. Unlike traditional streetcar systems running in mixed traffic, modern LRT street operation usually involves reserved lanes or transit-only malls. Occasionally, however, exceptions occur; thus, the Main Street light rail mall in downtown Buffalo, New York, was converted to general traffic in 2013–2014. Nevertheless, general traffic lanes are usually separated from LRT in city streets. Making such separation work (particularly if all trackways are paved) requires a disciplined and attentive motoring public and/or comprehensive enforcement.

Some of the more important systems adopting street running are briefly described. Calgary's C-Train, opening in 1981, was the first new light rail property to operate on downtown streets (*21*). One difficulty has been insufficient space at the high-platform stations for the many customers riding the system, particularly during rush hours. This is a cause for concern, because Calgary's LRT system carries even more passengers than Boston's. Calgary's 7th Street transit mall, which is shared with buses, handles a three-car light-rail train every three minutes during peak periods, enabling it to handle almost 10,000 LRT passengers per hour per direction. But assuming a speed of 7 to 8 mph in the transit mall, versus 12 to 15 mph in a subway, this implies accepting slower speed for lower capital cost.

Also opening in 1981 was the first new LRT system in the United States, the San Diego Trolley. This system was broadly similar in its design to Calgary, except that San Diego used low platforms. This avoided Calgary's problem with accommodating high-platform stations located on downtown streets. However, this marginally increased station dwell times, because San Diego's fleet was then comprised entirely of high-floor cars. All subsequent LRT systems in the United States using streets for downtown distribution have used low platforms as well, although Los Angeles, a high-platform system, uses reserved lanes in city streets on certain downtown approaches.

San Diego Trolley was noted for its incremental approach to system size and infrastructure provision (*22*). The first line was built with single track and strategically spaced sidings based on initially scheduled service levels. Subsequently, the line was double-tracked as ridership grew. The original CBD street running was supplemented by another distributor line on a railroad alignment on the edge of downtown in 1990, at a time when San Diego Trolley was adding new trunk lines.

Portland was another early light rail adopter, in 1986. Downtown street running was part of the incremental, economy-minded approach for Portland's MAX system, with speed being traded for economy in the central area. On the initial line, outlying stations were spaced about a mile apart, but stops in downtown Portland and the immediate approaches thereto were every 0.2 mi (*23*, p. 52). Although MAX is well patronized and highly regarded among transit professionals, slow speeds in and around downtown Portland may be among its greatest operating challenges. In 2009, MAX added a second downtown distribution alignment along a hitherto bus-only mall.

LRT came to Sacramento in 1987, where transit officials consciously chose economical access to downtown. Along the downtown streets where trains run,

> Two new pedestrian transit malls were…created. For its principal route into downtown, the light rail project…reconstructed five blocks [of a previously-existing mall on K Street] into a combined light rail and pedestrian mall. Along O Street, a second…mall was created on a street that had served principally as a parking street (*24*, p. 93).

In Baltimore, Maryland, where light rail opened in 1992, street running was chosen for cost reasons. Howard Street, the transit agency's choice for downtown distribution, "had been almost constantly disrupted by…[LRT] construction for years, and was avoided by most drivers" (*25*). An active freight railroad tunnel under the street complicated the tracklaying process. Howard St. runs north–south and crosses several major east–west arterials through the CBD, limiting the green phase available for LRT and adding to travel times.

Light rail opened in Denver in 1994 with a rather slow street running alignment through downtown (using LRT-only contraflow lanes) and a speed-restricted alignment at grade to the south through a major educational complex. For Southwest and Southeast Line riders, Denver's light rail makes up for its slow downtown access with a fast trunk to the south along a railroad alignment (*26*). An alternative downtown access route to Union Station opened in 2002 at grade, but this line was designed to serve additional central-area destinations rather than to accelerate operations (*27*, p. 39).

Dallas, where LRT opened in 1996, made a similar trade-off between cost and speed in order to make a new transit mode more affordable. Light rail runs on downtown streets, which have been turned into transit malls (*28*).

When the TRAX light rail opened in Salt Lake City, Utah, in 1999, there was ample room to situate the line in downtown streets. If anything, the wide layout of the streets presented almost the opposite situation compared to Boston and Philadelphia, which built subways because their narrow streets intensified CBD traffic congestion.

Most other new LRT systems, as shown in Table 1, have also placed light-rail tracks in downtown streets. Indeed, any other course of action has been exceptional enough to be worth noting.

New Subways

Only two new LRT properties built subways for downtown distribution (not counting trunk-line subways built in Buffalo and Dallas to reach downtown from outlying areas).

The first purpose-built subway was in Edmonton, North America's first new LRT system, which opened in 1978 (*29*). Edmonton followed the example of the Frankfurt, Germany, light rail operation fairly closely, including the choice of equipment and the use of a subway downtown. Although Edmonton's CBD was somewhat small for a subway, soil conditions were good for tunneling, and Edmonton's situation as a cold-weather city made its choice of a subway understandable (but Minneapolis and St. Paul, Minnesota, also known as cold-weather cities, subsequently built light rail with downtown street running). Nevertheless, the expense of Edmonton's downtown subway may have diverted resources away from subsequent expansion, with the result that Calgary, which used street running, had more resources for overall system expansion (*30*). As noted above, though, Calgary experiences slower speeds downtown.

Los Angeles was the only other new-start city to build a light rail subway downtown (*31*). With some 215,000 jobs in Los Angeles' CBD, there was a reasonable case for taking trains off the streets of the downtown core based on experience in San Francisco, Pittsburgh, and Philadelphia. Originally the subway, which opened in 1990, only served the Blue Line to Long Beach.

The light rail subway is quite short and serves only one station at Metro Center, where transfers may be made to a rapid-transit subway. An extension of the LRT subway is planned to Union Station, which is served by commuter trains and the light rail Gold Line. Los Angeles is the only U.S. city where light rail trains using streets have high platforms, and the resulting design blends urban design and traffic engineering considerations (*32*). In 2012 the Expo Line light rail opened to Culver City (and is slated to reach Santa Monica in 2016), using the Blue Line subway and approach to downtown Los Angeles.

Previously Built Subways

Two other cities might not have been able to justify new subways based simply on ridership and downtown size, but were able to reuse downtown tunnels previously built for other purposes. In St. Louis, the historic Eads Bridge over the Mississippi River and tunnel beneath downtown streets, originally built for railroad operation in the late 19th century, eventually became obsolete as railroad cars and locomotives became too large to fit. The bridge and the tunnel were rebuilt and retrofitted as the downtown distribution route for St. Louis' MetroLink light rail service, which opened in 1993 (*33*). Without the tunnel, a slower route with street running might have been chosen on cost grounds.

Downtown Seattle lies on a hill adjacent to the harbor, making up- and downhill travel challenging. To provide faster, more reliable downtown access, a tunnel for trolleybuses was opened in 1990. In 2005 the tunnel was closed for two years so it could be retrofitted for light rail. LRT service began in 2009.

Other Alignments

Most modern light rail properties operate in downtown streets and four others use subways, but one has a downtown operating environment that defies traditional categories. Charlotte's Blue Line serves the CBD, known as Uptown, at street level on a former railroad alignment. To better insert LRT into a busy business district and facilitate pedestrian access to stations, sidewalks have been provided on parts of this alignment, so that it partly resembles a transit mall. The existence of this railroad right-of-way was fortunate. The streets in uptown Charlotte, although on a grid, are somewhat narrow. Therefore, using city streets would have required removing lanes from traffic and finding urban design solutions to traffic engineering challenges.

EVALUATING TRADE-OFFS FOR DOWNTOWN ACCESS

One of the great strengths of LRT is that its right-of-way versatility allows it to be situated almost anywhere, including downtown streets, so that it may be built economically. At the same time, it is important to make light rail travel as rapid and reliable as possible within safety and capital cost constraints, to attract as many riders as possible. "System expansions can quickly reach a point of diminishing returns as new passengers at outlying stations face longer travel times to the urban centers" (*34*, p. 473). Sometimes, this dilemma can be addressed through operating improvements such as long station spacing, express trips, and skip-stop service.

Another way is to expedite operations downtown, where ridership and congestion are greatest, and stations are closely spaced. High-level platforms can help reduce station dwell time at busy downtown stations, assuming such platforms can be accommodated. Traffic signal priority for LRT at intersections could potentially reduce delays, although even under the best of circumstances, trains will necessarily experience delays at cross-streets. In certain situations, therefore, transit authorities might consider subways.

Capital costs of new construction are difficult to compare, due to inflation over time, the degree of competition for the services of construction firms, differences in costs between regions, and the individual requirements of specific sites (particularly soil conditions). Still, subways can cost about 8.5 to 10 times as much as street running. The expense of new subways helps explain why newer light rail systems have generally chosen street running for downtown distribution, making transit-only lanes or malls along downtown streets the default standard for new light rail systems.

There are, nevertheless, certain circumstances under which subways may be preferable to street running:

- Congestion on approaches to the CBD (such as bridges across rivers);
- Congested traffic and frequent traffic signals on downtown streets;
- Slow surface transit speeds, e.g., less than 6–7 mph (8.5–10 min per mi);
- Long CBD travel distances (usually more than a mile);
- Complex street intersections that limit the length of green-light signal phases;
- City blocks that are shorter than the maximum train lengths to be operated;
- High passenger volumes that intensify the travel times and the costs to passengers of slow LRT operation;
- High CBD employment levels, e.g., over 125,000;
- Future employment and activity growth in and around the city center; and
- Possible need for an additional downtown access line because the original line is nearing capacity.

In developing light-rail access to and through downtown, the goals should be fast, reliable service at minimum capital and operating cost over the foreseeable future. There are implications for transit agencies, their customers, and the communities that light rail serves.

Trade-Offs for Transit Authorities

For most transit authorities, the question is how to design, build, and operate systems that attract riders within the (often constrained) resources available. Downtown street running is easier and faster to build than a subway. On-street operation often frees resources that can be used to build more or longer trunk lines.

Operationally, however, subways can provide faster and more reliable service, because they are insulated from street-based disruptions such as traffic signal and street congestion and winter weather. On the other hand, maintenance and repairs are easier to perform on city streets than in subways.

Trade-Offs for Transit Riders

Transit riders seek fast, clean, comfortable, safe, and reliable service, to the extent that these characteristics can be achieved within financial constraints. Customer preferences are subject to a variety of localized circumstances.

Stations on city streets are easier for pedestrians to reach, and depending on local circumstances, can provide a greater sense of security (unless subway stations are well patrolled). When traffic congestion becomes intense, or when there are long approaches to downtown via city streets, the running time saved by using subways may more than make up for the additional walking time required to reach subway stations compared to more closely-spaced surface stops. Holding all else equal, inclement weather can make subways more attractive (as in Edmonton).

Trade-Offs for Cities

Finally, cities seek downtown renewal and related development and environmental benefits from light rail, again within budgetary limits. Many cities not in the first rank of population or downtown employment have been very receptive to on-street downtown access. The urban development effects of LRT are open to multiple interpretations and may have as much to say about the readiness of downtowns and other close-in neighborhoods for revitalization as they do about light rail's direct impacts. Nevertheless, there is enough evidence suggesting some manner of linkage between light-rail investment and urban development to interest cities in the development possibilities.

Some systems have experienced conflicts between LRT and pedestrians, and between LRT and motorists, particularly for left turns across the tracks when a train is approaching. These problems can be addressed to some degree through education, enforcement, and traffic controls, but they are unlikely to disappear entirely.

IMPLICATIONS AND OPPORTUNITIES

Developing subways makes sense when there is large downtown employment, street congestion on all available approaches, long segments with street running, and/or heavy ridership. Elsewhere, light rail's versatility allows transit agencies to locate it on downtown streets, thus making LRT feasible in cities where subways would be out of the question.

Today's largest and busiest LRT systems have developed incrementally over time. Generally, they start with a single downtown distribution route leading to an initial trunk line, and grow from there in multiple directions as traffic growth and popular demand warrant. Available resources are usually invested in trunk and branch lines beyond the CBD.

Increasing downtown size, traffic congestion, and LRT ridership may call into question the original cost-effectiveness rationale for street running in some cities. Modern street running was initiated largely to make light rail affordable, but it has costs as well as benefits.

> Street-running rail transit significantly reduces initial construction costs and the time needed to place a system in service. Costs for surface lines are about one-third of those for aerial lines and one-ninth of those for subways. The lower construction costs may…improve the cost-effective index.
>
> [However,] (s)treet-running…introduces another, somewhat disparate element into an already complex traffic stream. It poses potential problems of reliability, safety, lower speeds, and reduced capacities, especially in downtown areas.
>
> Street-running in the CBD and other congested areas, therefore, should be viewed mainly as the first stage of a future off-street, preferably grade-separated system. Incremental transitions to off-street operations should be achieved where time and cost constraints preclude grade-separated alignments initially (*35*, pp. 88, 95).

At the very least, transit agencies should seek design solutions that do not preclude subways in future decades. (Today's light rail subways in Boston and Philadelphia developed incrementally over many decades.)

In Los Angeles, rail transit plans include extending the existing Blue and Expo Line subway northeast from Metro Center to the Gold Line at Union Station. In approximate order of importance, these cities with street running may eventually wish to consider subways:

- Calgary, which has more light rail ridership than Boston, Los Angeles, or San Francisco (all of which have downtown subways);
- Portland, where long approaches to downtown on city streets reduce train speeds and reliability, and a second on-street downtown distribution line has been built;
- Dallas, which initially planned a subway but then chose to build in streets;
- Denver, where street running and other slow at-grade approaches to downtown contrast markedly with fast operations on the south trunk lines; and
- San Diego, where downtown growth has resulted in a second distributor line on the edge of downtown.

By contrast, street running may be better suited to systems with lower ridership levels, both because subways would be difficult to justify in cost–benefit terms and because lower-ridership systems are likely to serve downtowns where traffic congestion is manageable.

Once the decision has been made to build a new LRT system, there is much that the various stakeholders can agree on. As light rail is a lower-cost rail mode, suitable for any conceivable right-of-way (much like the early 20th century interurbans), it is not surprising that many newer properties use a combination of street running and traffic restrictions to create a street-level, pedestrian-oriented running way well suited for downtown distribution, if not always for speed.

At the same time, as cities grow and change, LRT may be subject to increased traffic congestion (which, ironically, may be a partial result of urban-renewal processes these lines have helped encourage). The cost ratio of about 9-to-1 between subways and street running certainly favors street alignments in many situations. On the other hand, the historical experiences of Boston and Philadelphia show that as central business districts grow and expand to take in areas beyond the traditional downtown core, transit systems can build shorter subways initially and expand them in subsequent decades as needed. Such a long-run approach could be useful for light rail cities with busier downtowns, as they seek to balance capital costs with the benefits of rapid and reliable service, especially through central business districts and their environs.

To conclude, there have so far been two best-practice models for downtown distribution for light rail. The first, which may be called Paradigm 1897, is exemplified by Boston. Its main features are

- Downtown distribution via subway, and
- Service to neighborhoods via street running or median-strip operation.

The second may be termed Paradigm 1981. Its best-known example is San Diego, and is characterized by

- Downtown distribution via street running (usually in a transit mall), and
- Private rights-of-way in outlying areas.

A new Paradigm two-thousand-something may be emerging in the coming years, as cities with Paradigm 1981 systems undergo continued regional and downtown growth. In this potentially emerging model, some of the busier Paradigm 1981 systems may find it advantageous to build downtown subways, thus combining elements of early and late 20th century practice to improve speed and throughput for light rail transit.

Downtown distribution for light rail today reflects a variety of historical experiences. Some systems may face important decisions over the next 20 or 30 years as their CBDs continue to grow. Downtown street running has made light rail affordable in many cities since 1981. Some systems, however, should rethink whether that paradigm still best suits their needs, as congestion makes subways increasingly attractive relative to their cost.

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METRO Green Line Transit Signal Priority
Implementation and Lessons Learned

DAN SOLER
Metro Transit

JONETTE KUHNAU
Kimley-Horn and Associates

The METRO Green Line [formerly Central Corridor light rail transit (LRT)] is the region's second light rail line (Figure 1). It links five major centers of activity in the Twin Cities region: downtown Minneapolis, the University of Minnesota, the Midway area, the State Capitol complex, and downtown St. Paul. The Central Corridor area is a highly built-up urban environment that imposes different planning and operational challenges than the Blue Line, the region's first light rail line, which operates in less densely developed areas for much of its length.

The Green Line has consistently exceeded ridership projections since it entered passenger service in June 2014, with more than 6 million rides in the line's first 6 months of operation. Average weekday ridership in November 2014 was 36,240, not far off the 41,000 rides projected for 2030.

Much of the Green Line route is in dedicated right-of-way in the center of University Avenue, a major east–west street between St. Paul and Minneapolis. This busy commercial corridor has high volumes of pedestrian traffic and is crossed by major arterial streets. Green Line trains pass through 68 traffic signals along the length of the alignment, with typical signal spacing of 300 ft in the downtown areas and one-quarter mile along University Avenue.

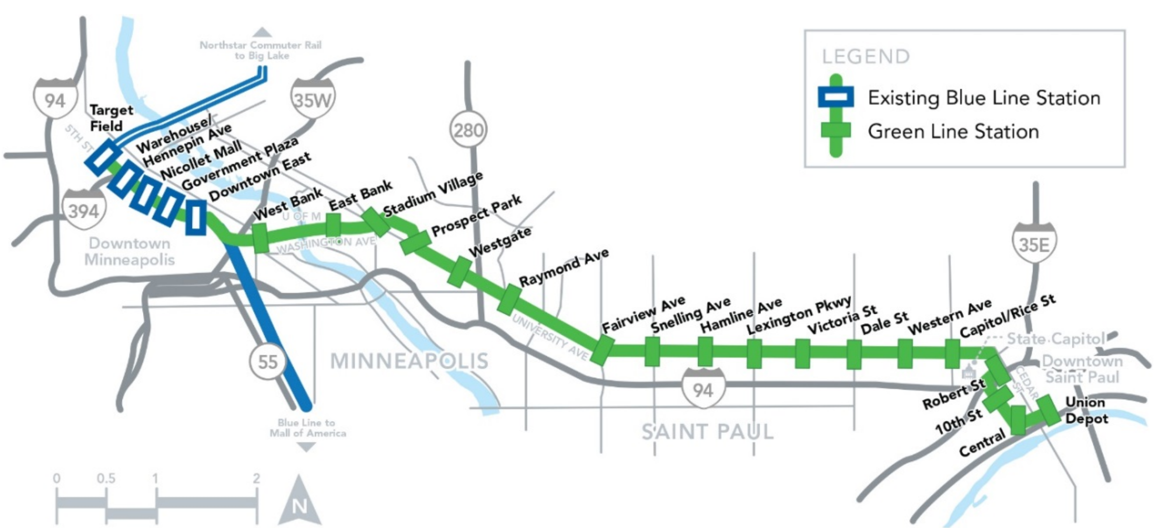


FIGURE 1 METRO Green Line route and stations.

When the Green Line opened in June 2014, the line's scheduled end-to-end run time of 48 min was based on a goal of no more than 8 min of total signal delay, which equates to an average of less than 8 s of delay per signal. The number of traffic signals that the Green Line must travel through, combined with the 48-min schedule, makes transit signal priority (TSP) critical to reliable, on-time service. Operating behind schedule not only impacts customer experience and satisfaction, it also results in additional operating costs when additional light rail vehicles must be introduced to maintain acceptable service frequency. TSP also provides opportunities for schedule recovery after minor disruptions.

Metro Transit faced several technical challenges in implementing TSP along the Central Corridor:

- The large number of closely spaced traffic signals include many intersections that have low traffic volumes on the cross streets;
- As required by the local agency, signal timing with TSP must serve all phases, maintain coordination, and provide pedestrian crossings every cycle, resulting in an available TSP time of roughly 10 s;
- Both LRT and street traffic need two-way progression; and
- If a train falls behind the signal coordination band, it will continue to fall further behind schedule at the downstream signals, until it can start a new coordination band.

The initial implementation of TSP under these conditions did not achieve the expected benefits in terms of travel time and reliability. Trip time measurements with TSP and optimized signal coordination showed that 20% to 30% of trains stopped at low-volume intersections and more than 60% of trains were stopping at medium and higher-volume signals.

Metro Transit's desire to reduce travel times and improve on-time performance led the agency to propose a new approach to transit signal priority that would better address the challenges of light rail operation in a dense urban environment. The search for a solution focused on University Avenue in St. Paul, where a large number of closely spaced traffic signals offered the potential for significant travel time improvements for the Green Line. Known as "predictive priority," this approach had three main objectives that were agreed to by Metro Transit and the City of St. Paul (the owner and operator of the traffic signals) (Figure 2):

- Maximize the opportunity for LRT to receive a green signal, based on the predicted arrival of the train at an intersection;
- Minimize disruption of signal sequence and traffic operations, especially skipping of phases; and
- Avoid causing significant additional delay to road vehicle or pedestrian signal phases.

An additional objective for the new TSP strategy was to minimize additional infrastructure cost by using the robust in-place LRT detection system, communications infrastructure, and traffic signal controllers that were installed as part of the Green Line project.

Predictive priority is based on the detection of a train at an upstream intersection, typically 25 to 60 s prior to arrival at the next signalized intersection. The advanced detection is received by the signal controller via the fiber optic communication network and is used to transition the signal timing, ending phases early or extending phases as needed, so that the signal will be "green" for the LRT phase at the expected time of its arrival. During the transition, the

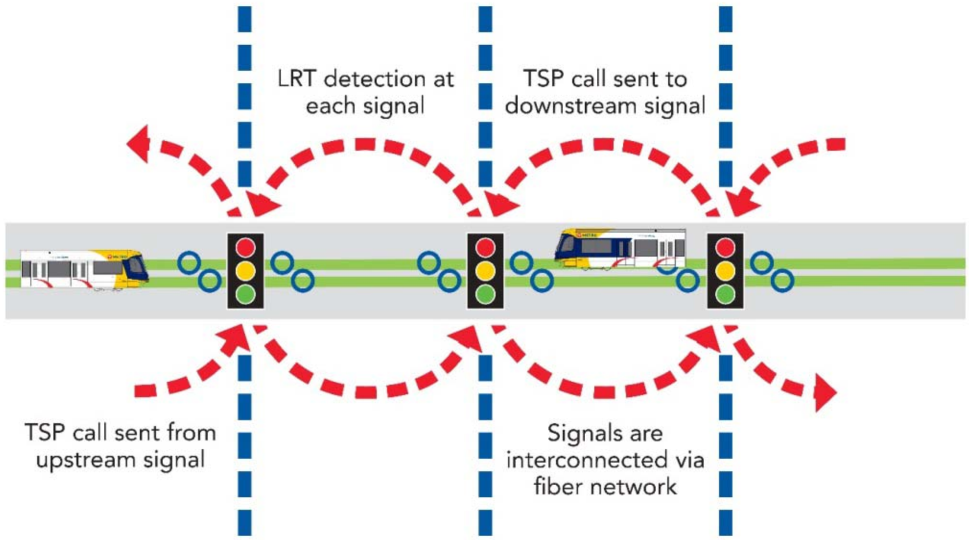


FIGURE 2 Schematic of predictive priority detection scheme.

controller uses logic within the controller, which was developed specifically for the Green Line, to continue to serve other vehicle and pedestrian phases until the train's expected arrival at the intersection. The logic was developed in close coordination and partnership with the signal controller vendor and required multiple iterations of testing to produce the final version that provided the desired operation of the vehicle, pedestrian, and LRT phases. Once the train arrives to a green signal indication and enters the intersection, the signal starts the clearance sequence to clear the LRT phase and transition immediately to other vehicle and pedestrian phases that have demand. If the train fails to arrive at the intersection within a set maximum time (typically 100 s), then the LRT phase will end and the train will proceed through the signal under the normal green band when it does arrive.

Using this method of signal controller logic, vehicle and pedestrian phases are not skipped, pedestrian clearance times are always served, and vehicles and pedestrians on the cross streets do not experience long delays as they would be expected to under a preemption scheme. In addition, emergency vehicle preemption (EVP) is assigned a higher priority than LRT and is allowed to override the predictive priority at the intersection. At the same time, nearly all trains are able to progress through the predictive priority intersections without stopping.

Prior to implementing predictive priority, the in-place vehicle detection was used along with new controller logic to monitor vehicle delay on the cross street and left-turn movements, as well as the pedestrian movements. The LRT detection was also used to track LRT stops, and the Metro Transit Automatic Passenger Counter (APC) system was used to track train travel times through the network. These vehicle, pedestrian, and LRT data were collected for a minimum of 36 h before and after predictive priority was implemented at each intersection. The data logs were used as a critical tool to evaluate whether the predictive priority was having the intended positive effect on LRT without negatively impacting vehicle and pedestrian delay. Extensive testing of the signal controller logic was also done with a full cabinet mock-up developed by the City of St. Paul, which was used to test numerous traffic and LRT scenarios and fine-tune the logic programming.

Data collected before and after the implementation of predictive priority showed that the percentage of trains stopping at predictive priority intersections was less than 5%, LRT trip times in the city of St. Paul were reduced by 10% to 15%, and on-time performance increased from 60% to 85% as predictive priority was implemented at 19 intersections along University Avenue from August to December 2014. Average travel times in St. Paul over this period were reduced from 34 to 35 min to less than 27 min, and variability in run times—a key factor in customer satisfaction—was significantly decreased. Delays for left-turning and cross-street traffic also declined, while average delays for cross-street pedestrians were generally similar to the before conditions. The Predictive Priority implementations were all done during the first 6 months of passenger service on the Green Line and were done without any interruption to service or additional equipment or infrastructure (Figures 3, 4, and 5).

Predictive priority is a data-driven approach to transit signal priority that relies on a robust detection system for both light rail vehicles and on-street traffic. Without accurate and reliable data, the controller logic needed to optimize signal phases and minimize disruption could not be performed. The approach also requires strong integration with traffic signal controllers, and Metro Transit's experience shows the benefits of involving signal controller vendors early in the process in order to maximize the capabilities of the controller software. Finally, it is critical to identify operational priorities and understand trade-offs between competing priorities when seeking to modify the signal operations strategies to accommodate a new mode.

The authors acknowledge the invaluable assistance provided by City of St. Paul Traffic Operations, Traffic Control Corporation, and Metro Transit Rail Operations in implementing transit signal priority on the Green Line.

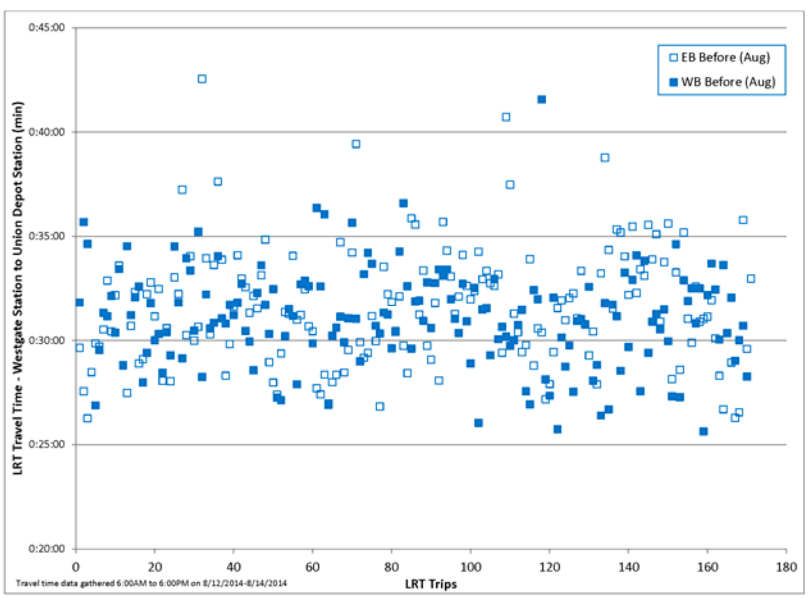


FIGURE 3 METRO Green Line LRT travel times before implementation of predictive priority TSP, August 12–14, 2014 (*n* = 171 eastbound, 169 westbound trips).

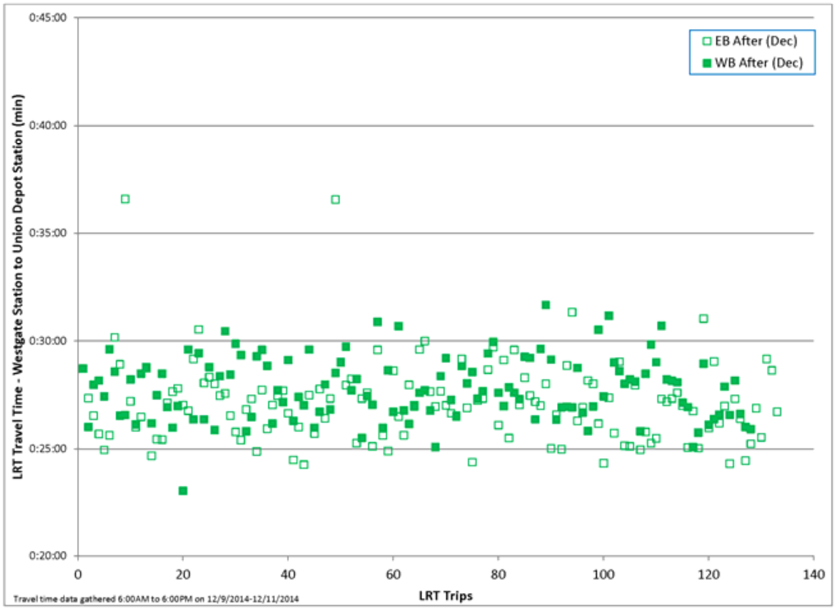


FIGURE 4 METRO Green Line LRT travel times after implementation of predictive priority TSP, December 9–11, 2014 (*n* = 132 eastbound, 128 westbound trips).

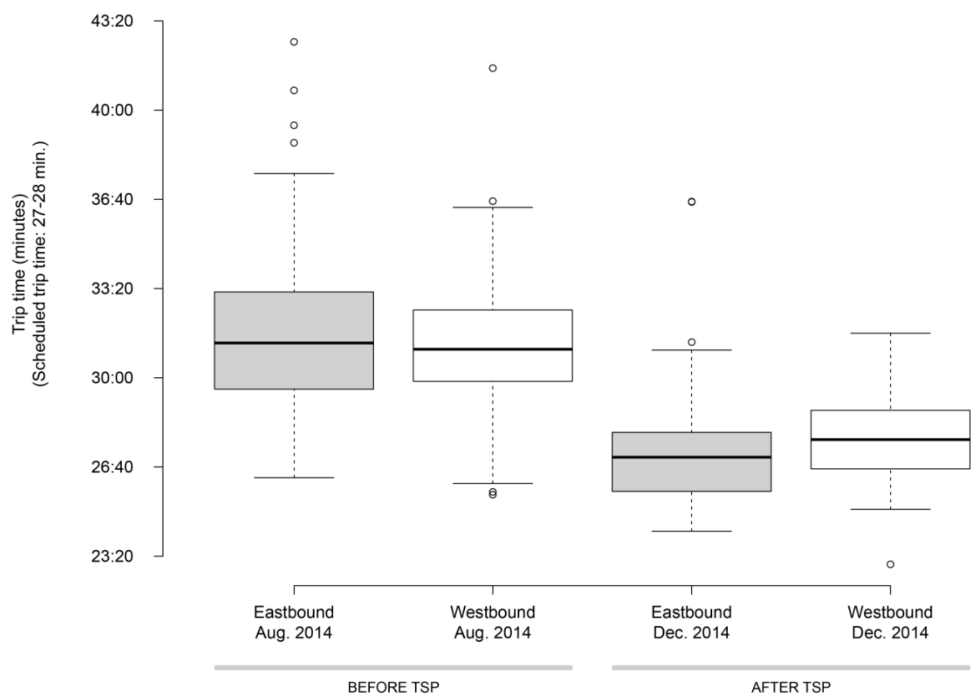


FIGURE 5 Comparison of METRO Green Line travel times before and after implementation of predictive priority TSP. Center lines show the medians; box limits indicate the 25th and 75th percentiles as determined by R software; whiskers extend 1.5 times the interquartile range from the 25th and 75th percentiles, outliers are represented by dots (*n* = 171, 169, 132, 128 sample points).

Expanding Metrolink Through Town Centers and Residential and Urban Environments Across Greater Manchester

JON LAMONTE
PETER CUSHING
ELIZABETH WEST
WSP Parsons Brinckerhoff–Transport for Greater Manchester, United Kingdom

Transport for Greater Manchester (TfGM) is delivering a £1.9 billion investment program that has already tripled the size of Manchester's iconic tram system, Metrolink. With nearly 35 mi of new extensions operating in a range of urban environments, this includes approximately 15 mi of new lines that are predominantly street running/run through the heart of regional town centers and heavily populated residential areas. This paper demonstrates the methods and strategies adopted by TfGM and partners to address the challenges of delivering new lines and operating in a constrained street environment. It outlines the experience gained for Greater Manchester in terms of the route design and integration with the urban realm, approach to construction, and stakeholder engagement. It is aimed at those who are involved in considering the development, delivery, and operation new light rail systems in urban environments.

MANCHESTER METROLINK

Greater Manchester's light rail system, known as Metrolink, opened in 1992. Metrolink was the first of the UK's second-generation tram systems at 19 mi and originally saw the conversion of two heavy rail lines connected by street running tramway directly through Manchester City Centre (Phase 1). This was later followed by a further 5-mi extension to Eccles in Salford (Phase 2).

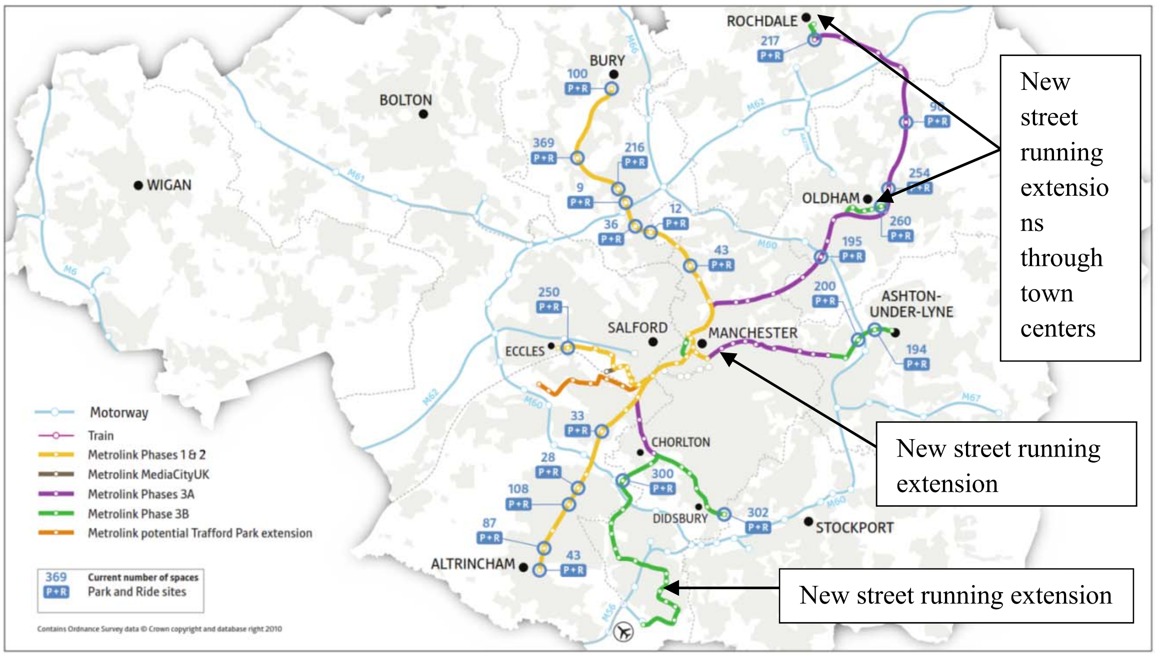
In the 1980s and 1990s the legal powers to further extend the Metrolink network were secured through either parliamentary acts or Transport and Works Act Orders (TWAO) (*1*). The strategy to expand the network is outlined in the local transport plan and subsequent updates 2 and 3 (*2*). Funding for the network extension was secured in two phases. Final funding for Phase 3a, approximately 19 mi of new tramway, was approved in 2008 with a mixture of national government funding, local funding, and prudential borrowing against the Metrolink revenues.

In 2009, the Greater Manchester Transport Fund (GMTF) was established, the first of its kind in the United Kingdom. GMTF is a Major Transport Scheme Prioritization and Funding Strategy established by the Association of Greater Manchester Authorities to locally fund £1.5 billion investment in transport projects across the 10 districts. This included the Phase 3b Metrolink extensions, a further 26 mi of new tramway, with final approval and appointment of the main contractor in 2010.

Metrolink Expansion

Totaling nearly 35 mi of new tramway, the Metrolink expansion has involved converting heavy rail and disused rail corridors as well as nearly 15 mi of either integrated on-street tramways or segregated on-street tramways as defined by the Guidance on Tramways Rail Safety Publication 2 by the U.K.'s Office of Rail Regulation (*3*). Figure 1 shows the Metrolink expansion program and summarizes the key features of each extension.

The extension to MediaCityUK spur was delivered alongside the 36 acre MediaCityUK mixed use development, home media companies [including the British Broadcasting Corporation (BBC)], ITV, and Salford University. The East Manchester line to Ashton and the Manchester Airport line are predominantly street running and comprise of a mix of integrated and segregated running. These lines run through a range of urban environments, including heavily populated



Line	Length	Stops	Park and Ride	Description	Opening
MediaCityUK	0.24 mi	1	N/A	Segregated street running	2010
East Didsbury	2.7 mi	5	300 space facility at East Didsbury	Conversion of disused heavy rail corridor	St. Werburgh's Road, 2011; East Didsbury, 2013
Ashton-under-Lyne	6.3 mi	12	200 at Ashton Moss, 194 at Ashton West	Mix of segregated and integrated street running	Droylsden, 2012 Ashton, 2013
Oldham and Rochdale, incl. Oldham and Rochdale Town Centres	14 mi	19	195 at Hollinwood, 250 at Oldham Mumps, 254 at Derker, and 217 at Rochdale Railway Station	3a: conversion of heavy rail corridor. 3b: mix of segregated and integrated street running	Oldham Mumps, 2012; Shaw and Crompton, 2012; Rochdale Railway Station, 2013; Oldham and Rochdale Town Centre, 2014
Manchester Airport	9 mi	15	300 spaces at Sale Water Park	Mix of segregated and integrated street running	2014

FIGURE 1 The phases of the Metrolink expansion and summary information for each line.

residential areas and suburban town centers. They also have complex interfaces with major stakeholders such as Manchester Airport, Network Rail, and Etihad Campus (home to Manchester City Football Club).

On the Oldham and Rochdale line, the Phase 3a extensions saw the conversion of the existing heavy rail line. Phase 3b saw the delivery of the ultimate aspiration to operate Metrolink directly through Oldham Town Centre (see case study below) and Rochdale Town Centre.

As well as the delivery of new tramway infrastructure, this expansion program also involved the construction of major new structures including superstructures on the airport line, to take the tram over the M60, Manchester's orbital motorway, and M56 as well as extensive highways remodeling. The TfGM team also delivered critical infrastructure ahead of schedule for other transport schemes adjacent to the Airport to reduce long-term disruption in the area.

Of note, this expansion program has been delivered on budget and with approximately 15 mi of new tramway delivered months ahead of public expectation. This included the Phase 3b extension from Droylsden to Ashton and the Oldham Town Centre extension becoming operational months ahead of customer expectations and the Manchester Airport line opening to passenger services over a year ahead of schedule. In addition, TfGM is currently constructing a new Metrolink line (Second City Crossing) though the retail, heritage, and business heart of Manchester City Centre. This primarily comprises integrated on street running through a mixture of highway and pedestrianized areas. TfGM has also secured funding the 3.3-mi Trafford Park line (TPL) extension, which is entirely street running. TfGM is currently in the process of securing the legal powers for this line.

These projects have given TfGM extensive experience of developing and delivering street running tramways, including managing extensive stakeholder interfaces, significant highway remodeling schemes, and the construction of major new structures in constrained urban environments.

Delivery Team

TfGM owns and manages the Metrolink network. RATP Dev Ltd is the current operator and also maintains Phases 1 and 2 (operator contract will be retendered in 2017). TfGM appointed Parsons Brinckerhoff, now WSP Parsons Brinckerhoff (WSP PB), as their delivery partner for the Metrolink capital program in 2007. The delivery partner is fully embedded in the client's organization with the TfGM/WSP PB team forming the Metrolink Integrated Delivery team (IDT).

MPact-Thales (MPT) was appointed in 2008 as the design, construct, and maintain contractor for the new extensions (until 2017). MPT is a consortium made up of Laing O'Rourke, Volker Rail, and Thales. Thales Transportation is also the signaling contractor for the new tram management system (TMS) that has been introduced across the network as part of the expansion program.

Literature Review and Methods

This paper outlines the direct experience of TfGM and its partners in delivering the street running sections of the Metrolink extensions in residential, town center, and city center environments. Relevant literature review has included referenced material, including TWAO applications and associated documentation, relevant planning applications, committee reports, and internal documentation.

IMPLEMENTATION

The strategic development of the Metrolink network is part of the wider, multimodal local transport plan (LTP) for Greater Manchester. This is consistent with National Planning Policy Framework and aims to deliver the transport element of the wider Greater Manchester strategy. LTP 3 (2011) reflects the strategic transport objectives set out in the Greater Manchester Combined Authority's Greater Manchester Strategy (2009 and subsequently 2013) by aiming to improve access to residential areas and to key education and employment areas.

Key issues and trends that informed LTP 2 and 3 have included increased levels of car ownership and congestion, alongside capacity constraints, on the rail network and, in places, ageing infrastructure and rolling stock. This is combined with poor levels of accessibility to employment, healthcare, and education in areas where there are high levels of noncar households. There are also areas of deprivation around the core of the conurbation that present barriers in terms of accessing work, healthcare, and education. LTP 2 and 3 also consider the economic growth anticipated from planned developments across the region. This includes the anticipated growth in jobs in the regional center, growth in jobs and passenger numbers at Manchester Airport, Trafford Park (the largest industrial estate in Europe), and the regeneration of town centers.

Light rail schemes typically serve high-demand corridors, nominally within 10km from the regional center. In practice, this can vary according to the specific nature of each line/scheme. This can include providing an attractive option for shorter journeys where other modes are hampered by congestion. Street running schemes offer the opportunity to provide direct connectivity to areas of high population and/or demand drivers such employment, leisure, or retail destinations that are not historically served by heavy rail. This enables tramways to play a key role in supporting regeneration schemes and major developments that support economic growth. The ability for street running trams to integrate into a highway environment and through pedestrianized zones also increases connectivity with key demand drivers. For example, street running tramways provide the opportunity to take customers right into and through the heart of town center and city center environments, as opposed to heavy rail stations, which typically terminate on the edge of regional and/or suburban centers.

Figure 2 shows the expanded Metrolink network in terms of connectivity to key demand drivers in terms of population and employment density as well as indices or deprivation and levels of car ownership, key issues for LTP 2 and 3.

Alignment Optimization

The concept alignment chosen for the tramway route is designed to optimize patronage by penetrating areas of high population and/or demand attractors, supporting redevelopment opportunities that bring further demand, interconnectivity with other forms of public transport, and providing an alternative means of transport to the private car.

A key factor for street running tramways is to optimize journey time and reliability to maximize the benefits of the scheme and provide an attractive alternative to car travel. TfGM's experience is that the optimum solution is to segregate the tramway from other traffic. This is a key consideration for the development of the scheme for the TWAO process. During this stage, the route and broad alignment of the tramway is determined along with the limits of deviation (LOD). The LOD is the maximum area within which a tramway can be built, and therefore this

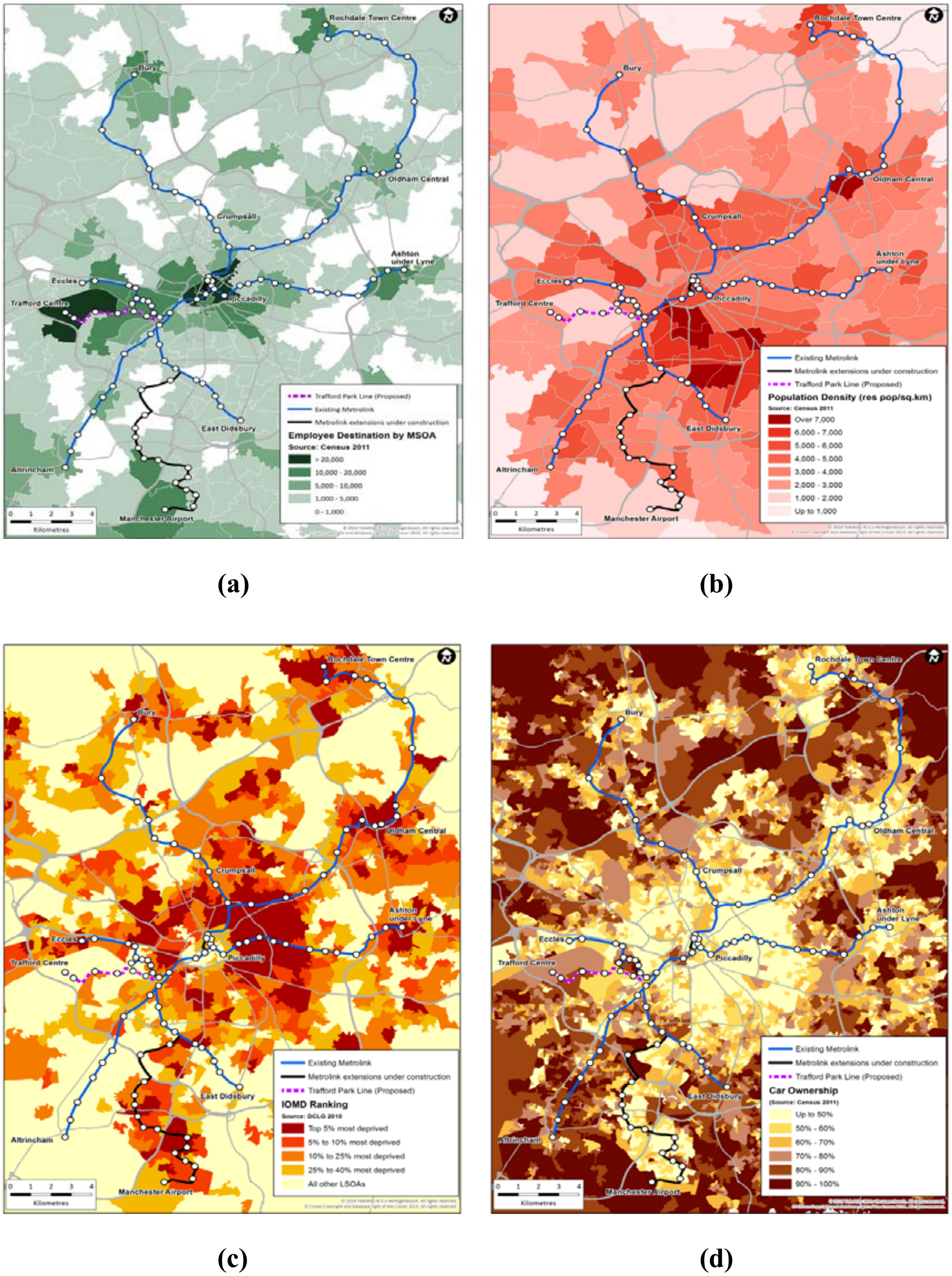


FIGURE 2 Expanded Metrolink (*a*) over the employee density areas; (*b*) over the population density; and (*c*) over the Indices of Multiple Deprivation (IOMD) ranking; (*d*) car ownership across the region. (NOTE: Maps produced prior to the opening of the Airport line, now operational. SOURCE: Based on 2011 Census data.)

stage needs to carefully balance the optimum alignment with compulsory purchase requirements. In most instances, the legal powers would also include the traffic regulation orders that were deemed necessary at the time of application.

This approach has been adopted for Metrolink where, under the legal powers, significant sections of the Airport Line and the latter half of the extension from Droysden to Ashton extension have reservations within the highway set aside for the tram. This has been central to the development of the TPL. This proposed line runs through Trafford Park, home to over 1,300 businesses and over 35,000 employees. This includes the Trafford Centre, the UK's second largest out-of-town shopping center, attracting over 35 million visitors per annum; EventCity, a 28,000 ft^2 exhibition center; and Old Trafford Stadium, home to Manchester United Football Club, with a capacity of over 75,000 people. As a result, the area suffers not only to day-to-day traffic congestion, but key seasonal peaks, such as the effects of Christmas shopping, and special events, including Manchester United football matches. This has led to the proposed TPL being almost entirely segregated from the highway to minimize the journey time, and importantly the reliability of the journey time, in order to offer a genuine, sustainable alternative to car travel (Figure 3).

FIGURE 3 Demonstrating urban realm integration at St. Peter's Square (*top*), and MediaCityUK (*bottom*).

It is not always possible to fully segregate the tramway because of spatial constraints, particularly in town and city center environments. In these instances, appropriate traffic management measures are developed and implemented, working with the local Highways Authority, to ensure tram priority while maintaining wider traffic flows and access. On the Airport line, this involved remodeling some 28 junctions, including implementing changes such as removing roundabouts and replacing them with signalized junctions. For 2CC there is simply insufficient space through the city center for segregated running. The scheme, therefore, includes a number of changes to vehicle traffic flows in the city to enable reliability for the tram services while still maintaining traffic flow and access. A series of measures, including pedestrianizing of roads, closure of junctions, and reversal of traffic flows on a one-way road, will be implemented. The highway arrangements were developed with Manchester City Council (MCC) to meet with the Transport Strategy for Manchester City Centre. This strategy aims to manage congestion by putting in place measures to discourage drivers using the city center as a "rat run" while still maintaining access for vehicles servicing or accessing business or amenities and therefore adding to the economic position of the city.

Integration with the Urban Realm

For Metrolink, the integration of the infrastructure into the local urban realm typically involves the renewal or reconstruction of the tramway corridor. This can bring wider benefits to the local community, for example, new urban realm, improved pedestrian and cycle routes, and the renewal/upgrade of the highway infrastructure as appropriate.

During the early stages of development for each of the extension, TfGM worked closely with the local authority to develop design guides for the project that ultimately became part of the main contract documentation. They articulated how the new tramways would integrate in the local environment and detailed the highway and pedestrian crossing layouts, stop platforms, landscaping, and urban realm, including paint colors, paving types, and street furniture design.

Civic Spaces and Developments

Where appropriate, the design of the tramway is tailored to fit within specific civic spaces or developments to create a seamless environment. An example is MediaCityUK spur and stop, where the finishes were specifically designed to blend in with piazza area and complement the overall urban realm. For 2CC, TfGM has liaised closely with MCC and their architects to ensure the tramway and new stop at St. Peter's Square integrates with the improved civic environment, demonstrating how street running schemes can integrate with and support regeneration schemes. A key challenge with this can be realizing an architect's vision for the urban realm, while still maintaining the Metrolink identity and standards of accessibility.

This is managed through close liaison and building a strong working relationship in conjunction with engagement with the Disability Design Reference Group.

Reducing Street Clutter

A key aim for local authorities is to reduce street clutter, particularly through new developments. Where possible, building fixings have been used as opposed to supporting the overhead line equipment (OLE) from poles. This reduces street clutter and lessens the visual impact on local buildings, particularly those of special architectural interest. It also provides cost, risk, and program benefits as, once legal agreements are in place with property owners, fixings are quicker to install and eliminate the risk of additional utility diversions. This approach is being used on 2CC, where building fixings account for 60% of the OLE supporting infrastructure. This has involved close liaison with MCC and heritage bodies to agree exact finishes where fixings are being applied to listed buildings. Where building fixings were not possible, particularly in residential areas, TfGM has worked with the local authority to use combined OLE and street lighting poles to reduce street clutter.

Construction

The delivery of street running tramways is ultimately a major, linear civil engineering scheme being constructed on the doorstep of residents and businesses including shops, restaurants, officers, hotels, and industrial premises and generally in the operational highway. This brings a myriad of challenges that are either not encountered in off street running or are intensified for on street trams.

Utility diversions are recognized as one of the highest cost and program risks associated with the delivery of street running tramways. This is due to issues associated with ageing assets, inaccurate records, uncharted services, and coordination of the numerous utilities contractors within the constrained highway environment.

For Phase 3, the diversion works has involved over 500 individual contracts, with a cumulative value of over £130 million and literally thousands of individual diversions through residential areas, the city center and town centers, and along the main arterial highway network. To manage this risk, a joint TfGM/MPT utilities team was established to coordinate procurement, cost management, and program. This team has built strong working relationships with the utility companies and achieved substantially reduced costs and timeframes through the following:

- Understanding, challenging, and realigning the operating procedures of each individual utility company, addressing their resource and procurement constraints;
- Placing core team resources inside utility company organizations to support their delivery;
- Challenging solutions and costs to achieve the best possible value for money outcome;
- Early procurement for long lead-time materials while designs were being finalized;
- Formalizing the alignment of the individual organizations with bespoke operating agreements; and
- Agreeing separate commercial and operating measures for mutual benefit.

On the Airport line, as an example, this culminated in a 9-month program saving and £10 million cost saving against original estimates. Other measures utilized include the following:

- Joint Utilities Group was established with representatives from TfGM, MPT, each of the utilities companies, local highway authority, and the Global Traffic Management contractor (see below). This group meets on a weekly basis to review progress; plan future works; and manage the complex interfaces between the works, main construction, highways, and stakeholders in a solution driven environment.

- Global Traffic Management Procedures were developed to simplify the multiple diversions being carried out by individual contractors in close proximity. This involved appointing a single traffic management company to design, establish, and maintain traffic management for all utilities works on the scheme. This integrated approach has improved safety and minimized disruption to the local communities.
- Uncharted services protocol was developed, agreed, and implemented with the utilities to facilitate the safe and speedy resolution of uncharted services. The protocol provides a commitment that uncharted services would be assessed and appropriate actions taken within 48 h of being identified, significantly reducing program risk. As a result, despite over 1,000 uncharted services encountered on the Airport line, this enabled construction to proceed and ultimately the new line opened over a year ahead of schedule.
- Innovative solutions have included accommodating new infrastructure and existing services using joint trench methodologies. This involves one contractor installing ducting and pipework for the different utilities in the same area. As well as efficiency savings, this significantly reduces disruption. This has been employed extensively on 2CC, where there are significant space constraints through the congested city center streets.

Track Construction Methodologies

In a street running environment, the approach to construction needs to consider impact on the local community, including access to properties, available space, and highway network. There is no one-size-fits-all approach; delivery of sections of the route must to be individually tailored to take into account their specific environment and constraints. Typical examples used for track construction on Metrolink have included the following:

- The "half-and-half" approach, where work sites are established on one half of the road to allow traffic to run on the adjacent lane under temporary traffic signal control. This enables efficient construction and maintains traffic flow. This approach was used on, for example, sections of the East Manchester line where there was not a suitable diversion route to support either a full closure or one-way system.
- Reducing the road width to a single lane and implementing a one way system. This enables access to local properties to be retained and provides greater flexibility and efficiency with construction sequence. This approach was deployed on, for example, sections of the Airport line, where an appropriate diversion route was available and agreed with the local highway authority.
- Full road closures with appropriate diversionary routes: This may be more disruptive in the short term but allows more efficient construction and therefore can reduce the duration of this element of the works. This approach has been employed on 2CC. To support the closure, servicing and access surveys were carried out and measures such as traffic and delivery marshals established to ensure deliveries to shops and businesses were maintained.

In each case, the length of the individual worksite is a careful balance between providing efficient construction while maintaining pedestrian and appropriate vehicle access to businesses.

Modular Stop Construction

During Phase 3, modular construction methodologies have been used for all of the 57 new tram stops. This approach involves off-site manufacture of specifically designed precast units that are assembled on site, reducing onsite tram stop construction time by 85%, while driving quality standards and consistency across the extensions. Environmental benefits include

- 50% reduction in site CO_2 emissions;
- 30% reduction in site water consumption;
- Over 50% reduction in construction waste arising; and
- Lower risks of local pollution incidents by the reduced build time with less disturbance to site neighbors, reduced vehicle movements, plant usage, and traffic congestion.

While this applies across the network, the benefits to the local communities are more prominent in constrained urban environments, where the benefits of shorter construction times, less vehicle movements, and reduction in general disruption are intensified. This approach won the 2012 British Precast Concrete Award for the highest levels of quality, innovation, and efficiency.

STAKEHOLDER ENGAGEMENT

The development and delivery of all the Metrolink extensions has been supported by a comprehensive approach to stakeholder engagement. However, this requirement is more intense for street running lines due to the proximity of the scheme to residential and commercial properties and the complex interfaces with businesses, road users, and pedestrians.

Local Authorities

The Metrolink street running extensions run through six different local authorities. Extensive engagement has been carried out at all levels and functions, in particular strategic management, planning, highways, regeneration, and neighborhood teams, to support the scheme development and delivery in line with program expectations. For example, regular meetings with planning departments to rehearse applications or the discharge of conditions in advance of formal submission have supported the approvals and consents process. Highways reference groups have been established to ensure the detailed design incorporates the Highways Authority requirements to facilitate technical approvals. An Emergency Services Reference Group has also been established to facilitate consultation with fire, ambulance, and police services.

Maximizing Accessibility for Disabled People

In 2008, TfGM established the Disability Design Reference Group (DDRG) to bring together members who represent a thorough cross-section of impairments, including wheelchair users, mobility scooter users, people with hearing and/or sight impairments, and people with learning difficulties. Through monthly meetings and site visits, DDRG provides a collective view on accessibility through design, delivery, and operation.

DDRG goes beyond compliance with legislation to identify practical solutions to remove barriers to accessibility by using the life experience and technical knowledge of disabled people. For the redevelopment of St. Peter's Square, DDRG influenced the architects design through the color/pattern for materials demarcating the tram swept path and the use of yellow handrails.

DDRG has been recognized as a model of best practice by the UK Equality and Human Rights Commission and won awards including Best Customer Initiative at the Light Rail Awards (2012), Breakthrough UK's National Independent Living award (2012) for public sector engagement, and the National Rail Award (2015) for "Putting Passengers First." Furthermore, TfGM is working with the Department for Transport and the Design Council/Commission for Architecture and the Built Environment to inform the next generation of guidance and standards based on the lessons learned from DDRG.

Wider Stakeholder Engagement

TfGM has a dedicated stakeholder engagement team for the Metrolink expansion program and has proactively engaged with residents and businesses in the vicinity of street running lines. This has included setting up a dedicated phone line and e-mail address for stakeholders to raise concerns, holding information events so the local communities can engage directly with the members of both TfGM's project team and the contractor. Through the expansion program, this has culminated in nearly 4,000 meetings, information events, and home visits alongside over 1,500 mail drops equating to millions of letters and communications with local communities.

Throughout construction, as part of the "no surprises approach," the team send regular letters to update residents and businesses about the works taking place in their immediate area, visit door to door, and attend public meetings and forums as well as using other communication channels, including media, social media, and websites.

This engagement has been carried out throughout scheme development and construction. For example, for 2CC and TPL, in addition to running high profile public consultations in support of TWAO applications, TfGM has ensured engagement with stakeholders along the route in advance of, during, and after the consultation to understand how businesses operate in order to inform the design. This has been key in terms of considering issues such as servicing and access and making refinements to the alignment to minimize the impact on businesses.

A key feature of this is that the stakeholder team are embedded in the Metrolink Integrated Delivery Team. This ensures that a stakeholder focus is maintained throughout the delivery team; both client and contractor and therefore stakeholder requirements are fed into the overall delivery approach and strategy. This is particularly critical in environments where there is a strong business interface; for example, suburban town centers and of course the city center where, for 2CC, business operational requirements have been built into the construction program and planning.

Another key feature of this is the relationship with the main contractor, MPT. While TfGM leads with stakeholder engagement, in practice a joint approach is taken to engagement and public liaison throughout the works. This ensures that the contractor has a direct understanding of stakeholder issues and therefore being able to make minor adjustments that have little impact on the construction program but can substantially minimize the impact on the local community. This may be the type of fencing used to maximize sight lines to retailers, assisting with deliveries to, in residentially areas, collecting bins on behalf of residents or providing special access arrangements for vulnerable individuals who, for example, need regular medical attention.

Bringing into Operation

A key challenge of bringing a new line into service is driver route training while maintaining operational passenger services. TfGM and MRDL have worked with a contractor to develop an innovative driver training solution, the Tram Pro Simulator. Unlike conventional cab simulators in the heavy rail industry, this uses gaming technology, video, and photography to simulate each line, including all relevant traffic and tram signals and signage. Unlike traditional simulators, up to eight drivers can be trained simultaneously, reducing training time in the cab from 9 to 1 h. Uniquely, the simulator also provides detailed analytics on each driver's performance.

This has specific benefits in a street running environment and is arguably safer as drivers are accustomed to the environment and road junctions in advance of interfacing with actual road users and pedestrians. It can also be used to simulate scenarios to assist with incident assessments and to retrain drivers as often as necessary without interrupting services. The Tram Pro Simulator is fully approved by the Office of Rail Regulation.

RESULTS

The Metrolink expansion program been delivered on budget with approximately 15 mi of new tramway delivered ahead of schedule. This includes the Droylsden to Ashton, Oldham Town Centre extension, and Manchester Airport, all of which are primarily street running. Indeed, the extension to Manchester Airport was delivered over 12 months ahead of public expectations. This success has also been recognized by a number of awards, including the National Rail Award for Civil Engineering Achievement, Light Rail Awards for Project of the Year 3 years in succession, Best Customer Initiative for DDRG, and industrywide recognition for the approach to utility diversions and the tram pro simulator.

This overall investment program has meant the network has grown from 19 mi with 26 stops to 60 mi with 92 stops. The capital program has also seen the expansion of park-and-ride facilities that has seen the number of spaces across the network triple. As a result, patronage has grown from by over 50% since 2011 and now stands at 31 million journeys per annum and growing.

As well as providing a frequent, efficient, and highly accessible form of public transport, the Metrolink extensions have demonstrated how they can support regeneration and economic growth.

For example, the Metrolink extension to Manchester Airport serves part of the package that supports Airport City, an 800m development the first of its kind in the United Kingdom, which will have 5 million ft^2 of development opportunities for offices, hotels, advanced manufacturing, logistics, retail, and leisure. The extension to MediaCity:UK, was again a key part of the transport strategy to support this major development. A Nationwide House Price Index special report in August 2014 indicated that properties within 500 m of Metrolink stop attract a 4.6% premium on average. Shortly after opening new extensions, for example to Manchester Airport, house prices were reported in the media to soar by 60% in areas adjacent to the new line.

Oldham Town Centre, Case Study

The Oldham Town Centre extension is a clear example of how introducing street running tramways can provide more than a new public transport service—it can support the transformation of a town center and the economic growth of the area.

Oldham was once described as the "most prodigious" mill town in Lancashire, and the "one that grew the quickest into the cotton spinning capital of the world." In 1871, Oldham had more spindles than any country in the world except the United States, and by 1909 was spinning more cotton than France and Germany combined. By 1928 it had reached its manufacturing zenith with more than 360 mills, operating night and day. Since the mid-20th century, Oldham has seen the demise of its textile manufacturing industry. An author on the depression that followed the slump in the textile industry remarked that "when the fall finally came, it was the town that crashed the hardest."

Oldham today is one Greater Manchester's largest suburban town centers, with a population of 224,900 (and over 100,000 businesses and 2.7 million people within a 30-min drive). Against a landscape of derelict mills, up to 2008 Oldham was served by a life expired, inadequate rail service outside the main town center. As part of the Phase 3a extensions, the original Oldham Loop Line between Manchester and Rochdale via Oldham was converted to Metrolink operation. In 2010, funding was confirmed for the main ambition to take Metrolink through the heart of Oldham Town Centre.

The Route

Leaving the main Oldham Rochdale line, the town center extension passes through a local business park with the first stop in a residential area adjacent to a local primary school. The new line then climbs a 6% gradient toward the A62 Oldham Way, the town center by-pass road. From here, the extension crosses a major traffic junction at Manchester Street and passes under Oldham Way, which was completely remodeled (Figure 4). It then continues through a new cutting toward the next stop and main town center area. The line then continues along the shopping thoroughfare, which includes the third stop within a pedestrianized zone. The final stop is in Oldham Mumps (see below), before the line rejoins the existing alignment heading north toward Rochdale.

The legal powers for Oldham Town Centre were originally secured under the Greater Manchester Transit System 1990 Bill 4/Act 1994. In order to meet the available funding parameters and support wider regeneration and economic growth, TfGM worked with Oldham Metropolitan Borough Council (OMBC) to develop revised proposals at both Manchester Street and Oldham Mumps. This involved securing two TWAOs to operate, while planning approval was sought to enable construction within the program constraints.

Manchester Street Roundabout

Under the original scheme, a tunnel would have been built to take the tram underneath Manchester Street roundabout all the way to the King Street stop. This costly approach had the potential to impact funding for the scheme and would also have been extremely disruptive. The revised proposal delivered better value for money as well as significant highway improvements, with the tram crossing the roundabout at grade and a new "cracked egg" new link road within the

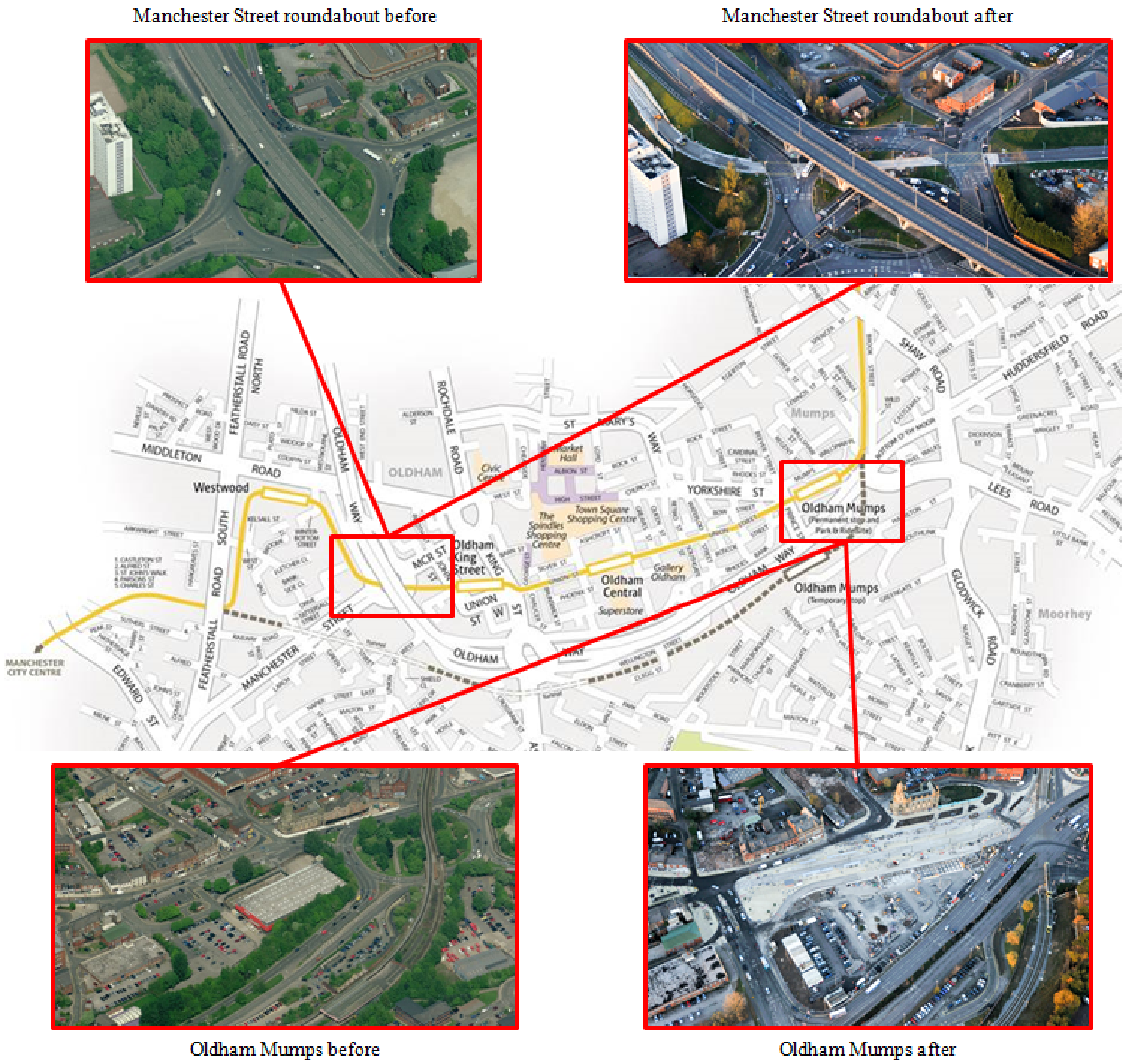


FIGURE 4 Map and photos showing the Oldham Town Centre extension.

roundabout enabling traffic from the southwest to turn right onto Oldham Way, without crossing the tram tracks. Traffic signals were also introduced to accommodate the tram and make the roundabout easier and safer for drivers to navigate. Pedestrians benefited from replacing unwelcoming subways with safer, more accessible controlled crossing facilities.

Oldham Mumps

This area is arguably the biggest transformation delivered by the Metrolink extensions to date. From the original station the heavy rail alignment ran over a large viaduct over the A62 that cut the town in half. With the funding approval in 2010, TfGM and OMBC worked together to take a holistic view to develop a solution that would maximize the benefits to the area. The old viaduct was demolished, opening up the entire area and making it a more attractive proposition for local developers. The roundabout was removed and replaced with a much more effective signalized junction with substantially increased capacity to cater for traffic volumes today and in the future. This also included a new link road into Oldham Town Centre as well as removing unpopular and unpleasant subways and replacing them with brand new, safer pedestrian crossing facilities.

Wider Urban Realm

The new line has completely rejuvenated the King Street area with an urban realm and planting scheme. The new line has improved pedestrian facilities with the highway being completely rebuilt from "back of pavement to back of pavement" with York stone in the conservation area and tree planters and landscaping at certain locations, new bins, and painting OLE poles in heritage green to match with the wider aspirations for the area.

The Outcome

Metrolink now provides a 12-min frequency, highly accessible service through the heart of the town center providing direct access to jobs, education, retail, and leisure in the town. It has also delivered a step change in the urban realm and the highways network.

On the opening of the Oldham Town Centre extension, Councillor Jim McMahon, Leader of Oldham Council commented, "Our wide ranging regeneration plans are designed to transform what Oldham Town Centre offers residents, businesses and visitors alike, and these will unashamedly capitalize on the arrival of the tram." This is coming to fruition with regeneration schemes, including a new sports center, Old Town Hall redevelopment, and new cinema complex and urban realm developments in retail areas adjacent to the Metrolink corridor. Of note is the Prince's Gate Development in Oldham Mumps unveiled in November 2014 (Figure 5). It will provide 150,000 ft^2 of retail space (attracting national retailers) and 800 quality homes and host a new supermarket tenant. Adjacent to Oldham Mumps Metrolink stop and utilizing redundant land from the original heavy rail alignment, the development will be accessed by the improved tram/bus interchange or via the new link road and highways improvements delivered as part of the Oldham Town Centre extension. This is expected to create more than 700 new jobs and could generate up to £21 million per year to the local economy.

CONCLUSION

TfGM's experience demonstrates that street running tramways can provide improved connectivity to key demand drivers, heavily populated residential areas, and/or high-demand destinations, serving areas that are not served by either existing or disused heavy rail areas.

It is noted that beyond the normal robust program and project management that would be expected for any infrastructure project, consideration does need to be given to the challenges and complex interfaces of street running tramways in order to ensure successful delivery within program and budget parameters. In TfGM's experience, these include consideration of the management of utilities, ensuring the construction works are planned with due consideration for reducing disruption to businesses, local communities, and road users. Proactive stakeholder engagement, including business and public liaison, is also essential for supporting the overall delivery program.

FIGURE 5 The top images show the original Oldham Mumps viaduct and heavy rail station; the middle pictures show the transformation of the Oldham Mumps area with the highways arrangements and the new stop; the bottom pictures show the tram on Union Street and the urban realm improvements at the King Street Stop.

The Metrolink extensions also demonstrate the positive impact that street running tramways can have in supporting regeneration, major new developments, and economic growth. Indeed, through the success of the Phase 3a and Phase 3b extensions, TfGM has been able to secure further funding to progress with the Trafford Park Line extension, which is currently progressing through the TWA process.

Metrolink is, and remains, Greater Manchester's flagship project for success in local delivery.

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Insertion of the Purple Line

MONICA J. MEADE
WSP Parsons Brinckerhoff

MICHAEL D. MADDEN
Maryland Transit Administration

Many cities in the United States have identified and used existing railroad corridors or wide roads for new light rail alignments. But there is a finite number of these corridors, and the expansion of light rail service will require the insertion of light rail into developed communities.

The Purple Line light rail project is notable because it is planned for a developed corridor in older inner- ring suburbs. The corridor is characterized by narrow curvilinear roads and a landscape of rolling hills and steep stream valleys. As a circumferential route crossing many of the major radial routes that lead to the center of Washington, D.C., there are few obvious large arterial roads that could accommodate the addition of a light rail line. This paper demonstrates some of the creative solutions specific to local conditions used on the Purple Line.

Inserting light rail into this environment requires ingenuity and full use of the operational flexibility of light rail as a mode. Different conditions in the corridor have been addressed with a range of design responses. This paper will describe some of the challenges faced by Maryland Transit Administration's (MTA's) planners and engineers and what design solutions have been proposed. There will also be a discussion of some of the tradeoffs to operations, travel times, or community impacts that were evaluated.

INTRODUCTION

Many cities in the United States have identified and used existing railroad corridors or wide roads for new light rail alignments. But there is a finite number of these corridors and as light rail is proposed in more cities in the United States, planners are faced with the fact that many of the easy projects have been built. The continued expansion of light rail lines will require the insertion of light rail into developed communities. An initial drive-through of a proposed corridor may raise the question: "Can it even be done without unacceptable impacts?" This paper demonstrates that with creative solutions specific to local conditions, it can be done.

The Purple Line light rail project is notable because it is planned for a developed corridor in older inner ring suburbs of Washington, D.C. (Figures 1 and 2). The corridor is characterized by narrow curvilinear roadways and a landscape of rolling hills and steep stream valleys. One of the greatest challenges to this project is that it is a circumferential route crossing many of the major radial routes that lead to the center of Washington, D.C. There are few obvious large arterial roads that could accommodate the addition of a light rail line.

Inserting light rail into this environment requires ingenuity and full use of the operational flexibility of light rail as a mode. In planning and designing the Purple Line, different conditions in the corridor have been addressed with a range of design responses. This paper will describe

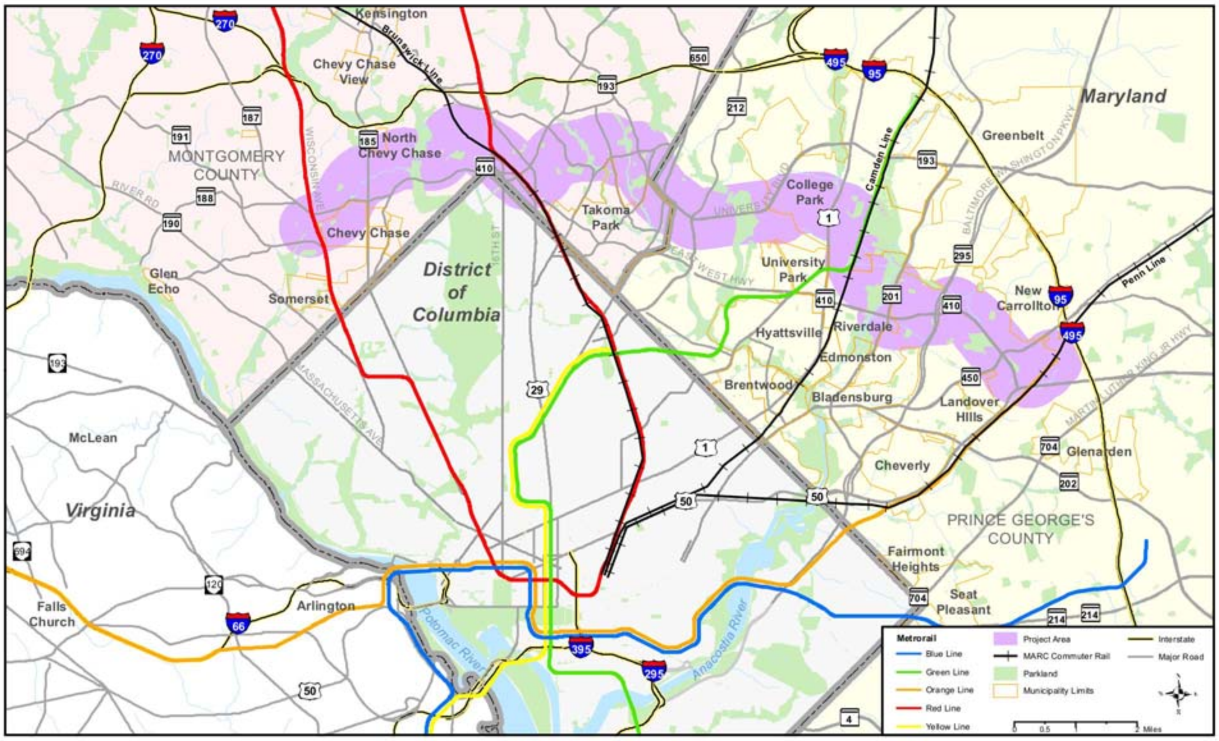

FIGURE 1 Purple Line in regional context.

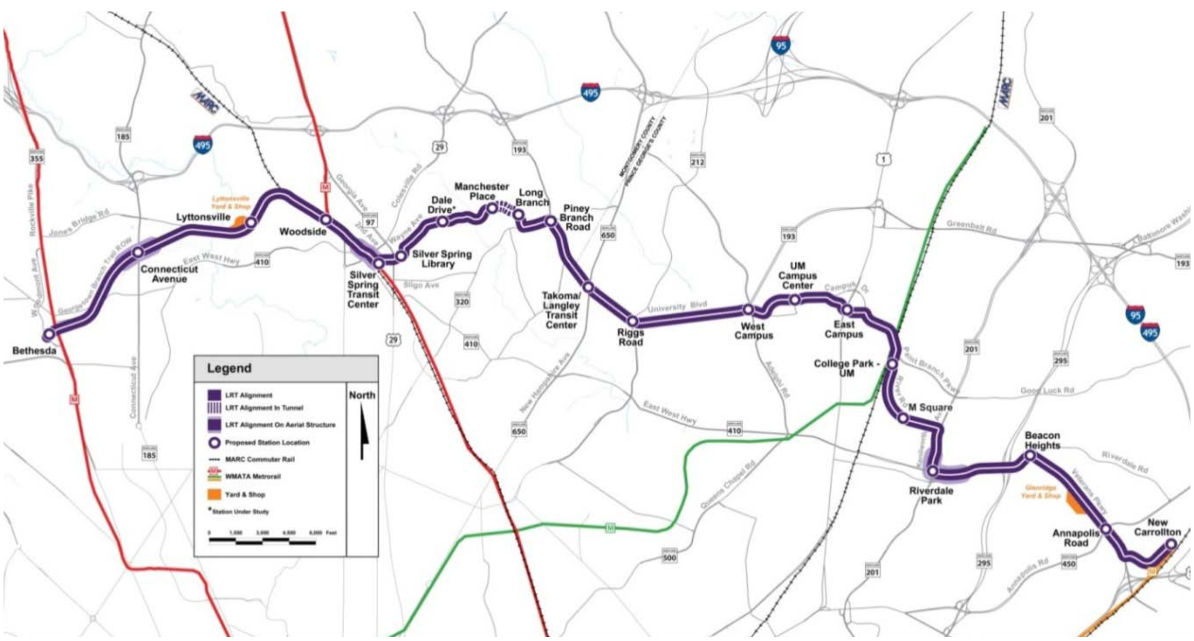

FIGURE 2 The Purple Line.

some of the challenges faced by the Purple Line planners and engineers and what design solutions have been proposed.

The Purple Line corridor is generally built out and is characterized by activity centers dispersed in communities, many of which are characterized by large trees and older homes. The land uses in the corridor are diverse. Some of these activity centers are densely developed, such as Bethesda, with high-rise residential and commercial buildings around the Washington Metropolitan Area Transit Authority (WMATA) Red Line Metrorail station, and Silver Spring, an older commercial area that has undergone extensive redevelopment in the last 10 years. Others areas are more purely residential, some wealthy and others not. The University of Maryland's flagship campus in College Park is a major employer in the corridor and home to over 37,000 students. Other areas provide opportunities for redevelopment or even new development. No single design characteristic would be appropriate for such a range of land uses.

The following are some of the challenges which have elicited creative solutions for the Purple Line:

- Narrow rights-of-way on residential streets of single family homes,
- Narrow streets of small businesses with limited parking and the need to provide for deliveries,
- Challenging new development constraining rights-of-way,
- Autocentric roadways lined with strip malls but characterized by high levels of pedestrian activity and the highest pedestrian crash rates in the state,
- Highly congested intersections through which the light rail vehicles must make a left turn, and
- Over many years of careful planning the MTA has come up with unique design solutions specific to each location and situation.

WAYNE AVENUE: MINIMIZING IMPACTS ON A RESIDENTIAL STREET

Narrow residential streets in communities of single-family homes require sensitivity to the fact that these are homes and neighborhoods. Property acquisition should be minimized or avoided. On Wayne Avenue in Silver Spring, MTA was faced with a four-lane street, with on-street off-peak parking. Local plans called for some widening of the road to add a 10-ft-wide multiuse trail adjacent to an existing sidewalk on the north side of the street with a 5-ft-wide landscaped buffer between the trail and the street. The county right-of-way is actually quite wide on this street, but most homeowners were unaware that much of "their" front yard was actually public property. MTA's initial plans were to widen the street by approximately 25 ft to provide dedicated lanes for the light rail. Realizing that the addition of the transitway (25 ft), the multiuse trail (10 ft), and the landscaped buffer (5 ft) would have extensive impacts on the neighborhood with over 40 ft of widening, MTA began to look for ways to minimize the widening. The first was to meet with the local county about the trail, the sidewalk, and the buffer. Montgomery County agreed that a narrower combined sidewalk and multiuse trail would acceptable in this area and would meet county standards as defined in the *Countywide Bikeways Functional Master Plan*. An 8-ft trail/sidewalk was proposed, with a 5-ft landscaped buffer. A 5-ft buffer provides enough space to plant trees, not simply shrubs or other smaller vegetation. The roadway configuration was the next challenge. MTA's preferred arrangement is, of course, dedicated transit lanes without interference of vehicular traffic; however, compromise is sometimes the best approach to minimize community disruption and public (and likely political) opposition. MTA evaluated whether the Purple Line could operate in mixed-use lanes to avoid extensive widening for the full length of the street. MTA did a detailed traffic study to assess the impacts, both to general traffic and to light rail operations. The findings of the study were that the traffic delays (and future light rail delays) would be from the left turns. If left turns could be eliminated or accommodated, traffic operations would actually improve over the No Build in 2040. MTA proposed adding left-turn lanes at the signalized intersections, thus allowing MTA to maintain the existing four lanes for most of the street and to minimize private property acquisition and widening. The most widening will be at the intersection with the median station platform. However, the station platform will provide a pedestrian refuge, mitigating concerns about some pedestrians finding the street too wide to cross in one signal phase.

DALE DRIVE STATION: SAFETY CONCERNS ABOUT MEDIAN PLATFORM

The Dale Drive Station on Wayne Avenue is a center platform station located in the middle of the street, just east of the intersection with Dale Drive. The light rail vehicle in the eastbound direction will operate in a shared lane while the light rail vehicle in the westbound direction will transition into a dedicated lane approaching the station platform. The westbound light rail vehicle will move on a queue jump signal phase after stopping at the station platform prior to the westbound through-movement signal phase.

This configuration was the result of the added left-turn lane for westbound traffic that protected vehicles making left turns from conflicts with general traffic, and mitigated traffic interference with light rail operations. MTA doesn't have any similar conditions on the Baltimore Central Light Rail and concerns were raised about having a center platform with the adjacent eastbound mixed-traffic lane. The fear was that an uncontrolled vehicle would strike someone on the platform. MTA conducted a hazard analysis and as part of this, reviewed other light rail system stations with mixed-use traffic lanes abutting platforms. The other LRT systems reviewed were

- San Francisco MUNI Third Street Line (T), Revere/Shafter Station;
- San Francisco MUNI Market Street Line (F), 16th and Noe Station;
- New Orleans Street Car, Carrollton Avenue Branch, Bienville Avenue Station; and
- Sound Transit LRT in Tacoma, Washington, Convention Center Station.

No extraordinary safety measures were noted for these systems. MTA decided to design the travel lanes with tactile demarcation or rumble strips closest to the platform so car drivers will be alerted to their proximity to the station platform (Figure 3).

FIGURE 3 Dale Drive Station showing rumble strip at platform.

BONIFANT STREET: MINIMIZING IMPACTS TO SMALL BUSINESSES ON A NARROW STREET

In another area the Purple Line will operate on one block of a narrow street of small independent businesses (Figure 4). The street is currently approximately 48 ft wide and operates as a two-way street with metered parking on either side. The local businesses were justifiably concerned about how the Purple Line would impact their business operations. The two main issues were loading areas for deliveries and parking.

Small businesses often depend on the presence of on-street parking for their customers' use. In fact, studies have shown that there does not need to be enough on-street parking for all the customers but rather the perception that there is parking. This area has many public parking garages and surface lots maintained by the county, one lot actually in this block. MTA proposed making the street one-way with an 11-ft travel lane and maintaining the parking on one side of the street. The traffic pattern along Bonifant Street east of Georgia Avenue will be modified to only allow one-way traffic coming in from Georgia Avenue; heading east on the east side of Georgia Avenue. A total of 8 on-street parallel parking spaces will be provided on the south side of the street in addition to 4 parallel spaces provided adjacent to the plaza area at the Silver Spring Library building. The design along Bonifant Street was optimized to avoid reconstructing the existing sidewalks.

The direction of the street would be one-way eastbound from the major arterial at the end of the block, making it easy for customers to enter the street. The plans would eliminate the parking spaces on the north side of the street. The small surface lot (22 spaces) was found to be metered for long-term commuter parking (9-h meters), despite the fact that there are a several large county-owned garages intended for commuters in the area. The county agreed to change the meters in the lot for short-term parking. This addressed the issue of parking.

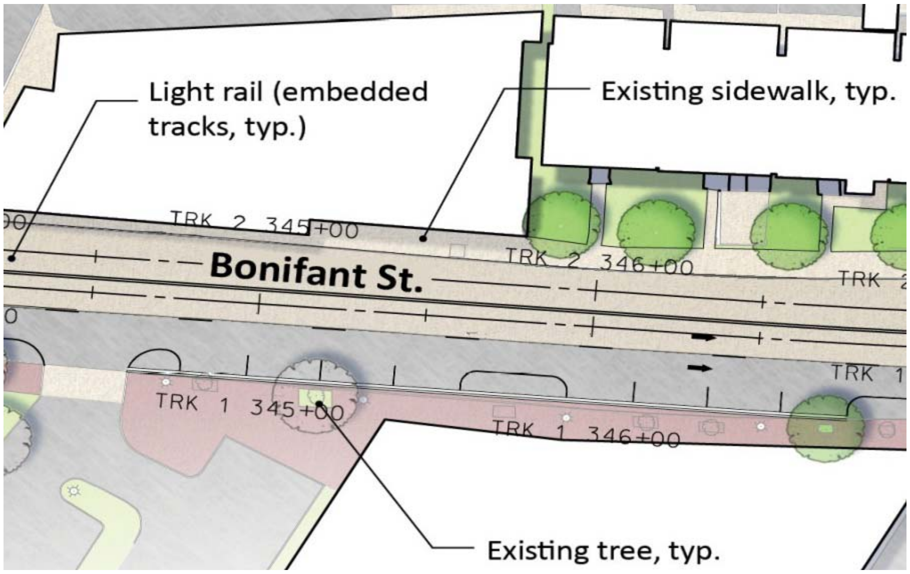

FIGURE 4 Bonifant Street lane configuration detail.

There remained the question of how these small businesses would receive deliveries. Most of the stores do not have an alley behind them providing for rear deliveries; deliveries are made from the street. Because the street would now be one lane wide, there was no provision for delivery trucks to double park if empty parking spaces were not available. As a solution, and based on discussions with Montgomery County, Bonifant Street east of Georgia Avenue will be restriped for two eastbound lanes and parking. The northernmost eastbound lane will be shared with the eastbound light rail vehicle and will be used as a left turn lane into the two existing alleys and to bypass any double parked trucks that may be blocking the right lane. The low level of traffic on the street will make this a relatively rare occurrence, but one that could alleviate potential problems for local traffic and local businesses.

At the end of the block described above, the Purple Line needs to travel north for one block and then turn east on to another street. These would have required quite constrained turns on narrow roadways, with right-of-way and traffic impacts. However, the large parcel at the end of Bonifant Street was proposed for a new county library (Figure 5). The optimal alignment for the Purple Line would be a gentle turn through the parcel and then a gentle turn to the right at the intersection.

SILVER SPRING LIBRARY: INTEGRATION WITH NEW DEVELOPMENT

Working closely with the county a dramatic plan for the alignment was proposed, with the library building built up and over the light rail trackway. The Silver Spring Library Station is a side platform station situated within the envelope of the new Silver Spring Library (Figure 6). The track alignment through the station area is not parallel to the building walls that face them, resulting in tapered platforms at track 1 and 2. The track 1 platform is at its widest point of 13 ft 3 in. at the eastern end and accommodates an American with Disabilities Act–compliant ramp and stairs; its narrowest point at the western end is 8 ft 3 in. Conversely, the track 2 platform at its widest point to the west is 18 ft 8 in. and 7 ft 4 in. at its narrowest point to the east.

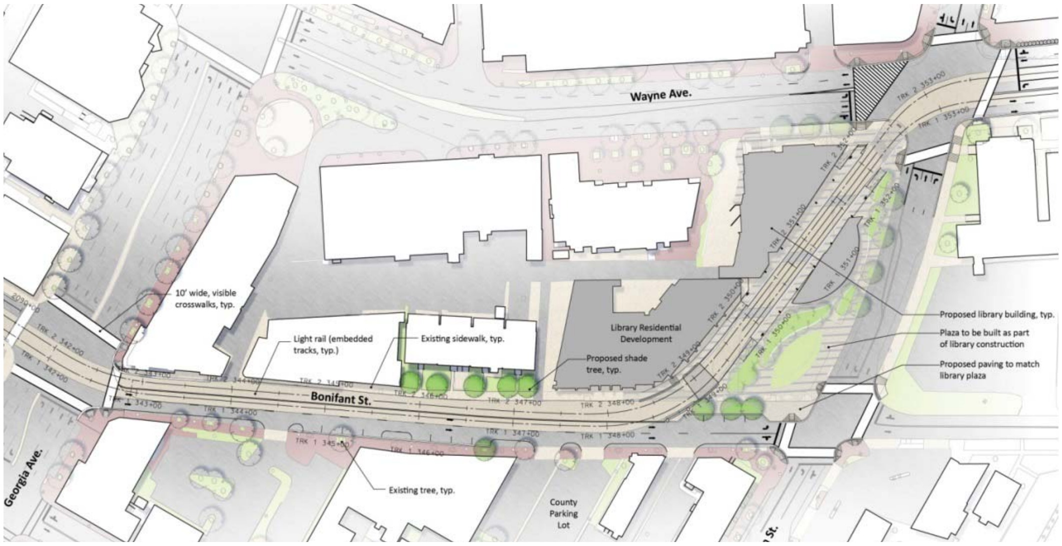

FIGURE 5 Bonifant Street and Silver Spring Library.

FIGURE 6 Silver Spring Library showing future station.

The cast-in-place concrete platforms are surfaced in diagonally arranged precast concrete pavers in a running bond that match the contiguous pattern established in the plaza; the alternating accent stripes of the plaza terminate at the platforms as to not create visual confusion within the station area. The vertical faces of the platform edges are finished in full-height granite blocks that butt into the tactile warning strips. Pedestrian access is via at-grade walks and track crossings connecting to adjacent sidewalks. Queuing rails and tactile warning strips differentiate areas of pedestrian passage along the tracks, from the adjoining landscaped plaza and sidewalks as to clearly define areas of caution.

The overhead wire system attached to the underside of the building eliminating the need for poles. The landscaping and hardscaping of the plaza and station area are being designed to create a signature space. This station is truly unique and beautiful and will be one of the highlights of the Purple Line.

UNIVERSITY BOULEVARD: SUPPORTING LOCAL PLANS FOR FUTURE TRANSIT-ORIENTED DEVELOPMENT

The three examples above are all different ways to insert a light rail line into a narrow constrained right-of-way, minimizing impacts to existing properties. But in other areas of the Purple Line the right-of-way is wide and expansive. University Boulevard (MD 193) is a 6-lane state highway characterized by strip shopping centers and other autocentric uses (Figures 7 and 8). In some areas there are adjacent service roads resulting in an even wider transportation corridor. The other land use in this area is residential, with older garden apartments and some areas of small single-family homes. This area has long been a commercial center for recent immigrants. The majority of the residents and businesses are now Latino, but there are West African, Vietnamese, Indian, and Caribbean businesses and residents as well. This is an area of heavy pedestrian activity, despite its autocentric character; and in fact, because of that character, it has a very high rate of pedestrian injuries and fatalities. The blocks are long, and the roadway is wide, and pedestrians regularly cross this busy roadway midblock. Transit use in the area is high, although the Metrorail system does not serve this area. The Purple Line, providing reliable access to the Metro system, will be a major boon for the area.

The local counties and the State Highway Administration have been working to make the area safer for pedestrians, generally by adding median fencing in the roadway to prevent midblock crossings. Widening the roadway to add two lanes for the Purple Line to this roadway (and more for the station platforms) would create an even less pedestrian-friendly environment. The local land use planners' vision for this roadway was to make it more attractive and safer, with wider sidewalks, landscaped buffers, and cycle tracks. They envisioned a typical transit-oriented streetscape with buildings closer to the road, and the removal or relocation of the large parking lots. Clearly the addition of the Purple Line, requiring close to 30 ft of additional right-of-way width, just for the trackway and center catenary poles (used in this segment because of the width of the roadway) would not contribute to this vision. Working with the State Highway Administration, MTA began to investigate the consequences of converting the two center traffic lanes into dedicated light rail lanes. This would minimize the additional right-of-way needed, leaving more room for wider sidewalks and landscaping. The three station platforms in this two-mi stretch of the alignment would provide pedestrian refuges for those who could not cross the road in one signal phase. The Purple Line could be used to enhance pedestrian safety, and the new sidewalks and landscaping could improve the aesthetics of this rather dilapidated corridor. Convincing the State Highway Administration to convert two travel lanes required detailed traffic studies, analysis of average daily traffic trends, as well as much discussion of the opportunities for improvement of pedestrian safety. After construction of the Purple Line the typical section along University Boulevard will consist of two 11-ft vehicular through lanes in each direction. For outside vehicular through lanes, an additional foot is provided for the gutter pan. The conversion of two through lanes to light rail lanes was done in order to minimize displacements, property impacts, and cost and to improve pedestrian safety.

Ultimately the rebuilt roadway will include two 11-ft through lanes, 5-ft in-road bike lanes, wider sidewalks near stations, a landscaped buffer between curb and sidewalk where

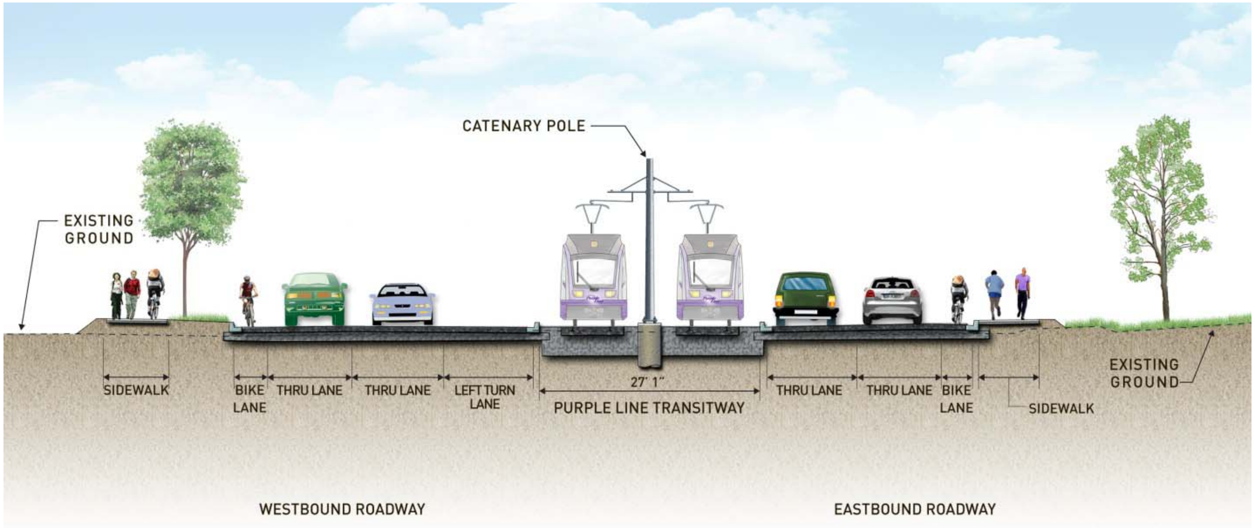

FIGURE 7 University Boulevard typical section.

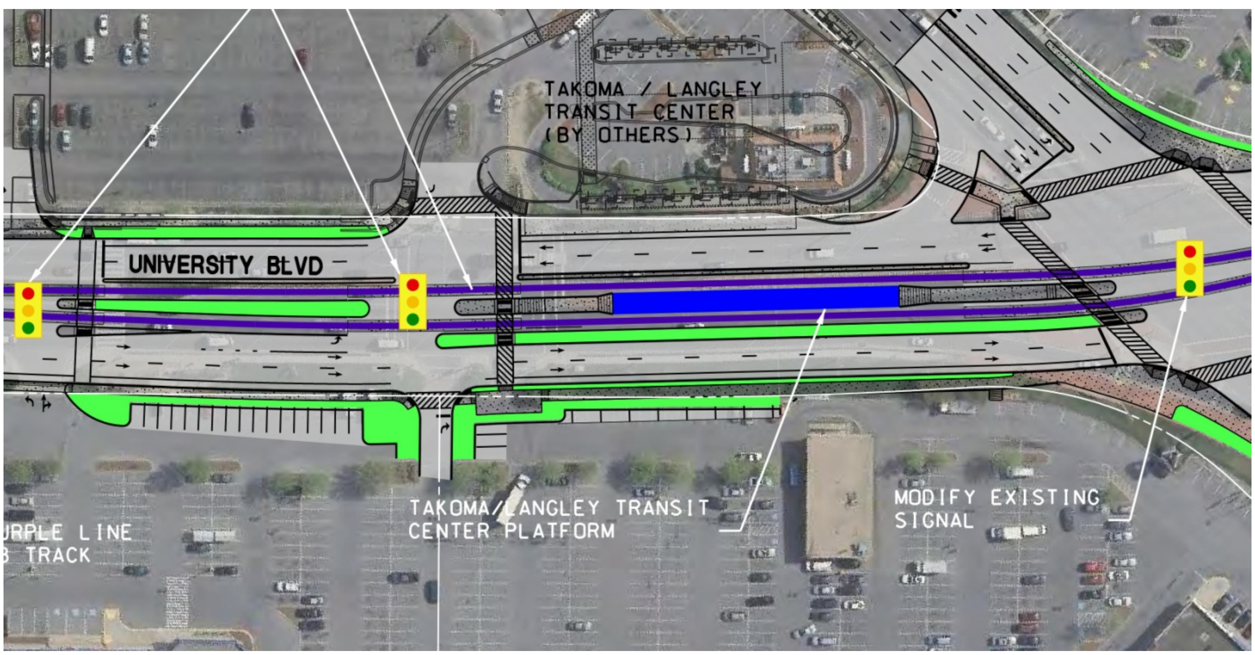

FIGURE 8 Takoma–Langley Transit Center station plan showing crosswalks at stations, landscaping areas (in green).

practical, larger pedestrian waiting areas at intersection crosswalks near stations, additional crosswalks at signalized intersections, and refuge areas in most crosswalks. At some intersections left-turn lanes will be provided to maintain traffic. Fencing to control midblock crossings will be maintained in key areas. As is the case throughout the alignment, bicycle storage racks will be provided adjacent to station areas.

UNIVERSITY OF MARYLAND: DESIGN SOLUTIONS FOR A CAMPUS

The Purple Line will pass through the large campus of the University of Maryland at College Park, providing a much-needed transit connection to the region and the Metrorail system. The street the Purple Line will use is Campus Drive, the main east–west road through campus (Figure 9). It is also used as a cut-through by local drivers. The current configuration is mostly two lanes, with a bus pullout. The average daily traffic is not high, about 7,000 vehicles, approximately 10% of which are buses (both University-operated and local), but there are 25,000 pedestrian crossings daily. MTA worked closely with the University's Facilities Planning group evaluated several options: a four-lane configuration to provide two transit lanes (light rail and bus) and two general traffic lanes, a three-lane option with two transit lanes and a one way general traffic lane, and a transit-only option, with just two lanes.

The university would like to reduce traffic through the center of campus, and the campus master plan envisions a pedestrian zone in the heart of campus. However, the university is not yet ready to completely close this roadway to general traffic. The three-lane option will reduce the amount of general traffic through the heart of campus. The two outside lanes are 13-ft transit lanes, wide enough to accommodate the light rail and buses, and an 11-ft middle lane that will serve as a one-way through lane. The university will be able to manage this lane, reversing the direction, for example, after football game to expedite the departure of the fans from campus. Ten-foot sidewalks and a separate 10-ft bike lane will be built as well. If the University does decide to completely eliminate general traffic on this street in the future, the center lane could easily be converted into a landscaped alley or a pedestrian walkway similar to the pedestrian area on University Avenue along Metro Transit's Green Line through the University of Minneapolis.

The sidewalks are proposed directly behind the curb in order to minimize the width of the roadway typical section. Where space is available, a 7-ft landscaping buffer is provided in order to provide additional separation between the pedestrians and the embedded track (not shown in the rendering below). A 10-ft-wide dedicated bicycle lane is located along the eastbound side of the roadway.

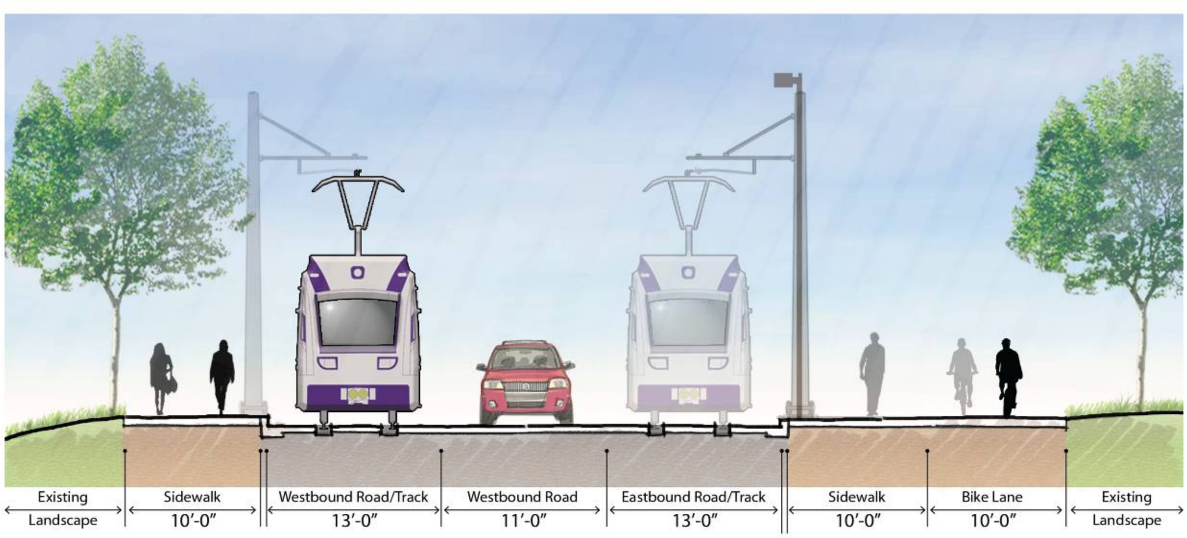

FIGURE 9 University of Maryland Campus Drive typical section.

COLLEGE PARK UMD METRO STATION: CONNECTIONS TO EXISTING METRORAIL STATION

An important goal of the Purple Line is to provide easy convenient connections to the existing Metrorail system. This presents a variety of challenges because the Metrorail stations vary so widely. In Bethesda the Metrorail Red Line station is underground. The Bethesda Metro station currently has only one entrance, at the northern end of the platform, but the Purple Line will be directly above the southern end of the platform. A new entrance to the Metro at this location is needed as ridership has grown since the opening of the station 30 years ago in 1984. This new entrance with high-speed elevators will serve the Purple Line as will, providing easy transfers between the two lines. In Silver Spring the Purple Line station will be built on an aerial structure immediately adjacent to the aerial Metrorail station with elevators, stairs, and escalators. At the College Park UMD Metrorail station WMATA owns several parcels of land between the station and the road. Currently undeveloped, WMATA plans for commercial development at the site directly in front of the station and residential development immediately south of the commercial site. MTA coordinated with WMATA's real estate department and located the Purple Line tracks immediately adjacent to an existing parking garage and then very close to the Metrorail station and tracks (Figure 10). The Purple Line tracks and station will be parallel and adjacent to the Metro tracks, at the back of the undeveloped residential parcel (next to the planned residential parking garage). This avoids concerns about noise, access, or visual impacts to the residential development.

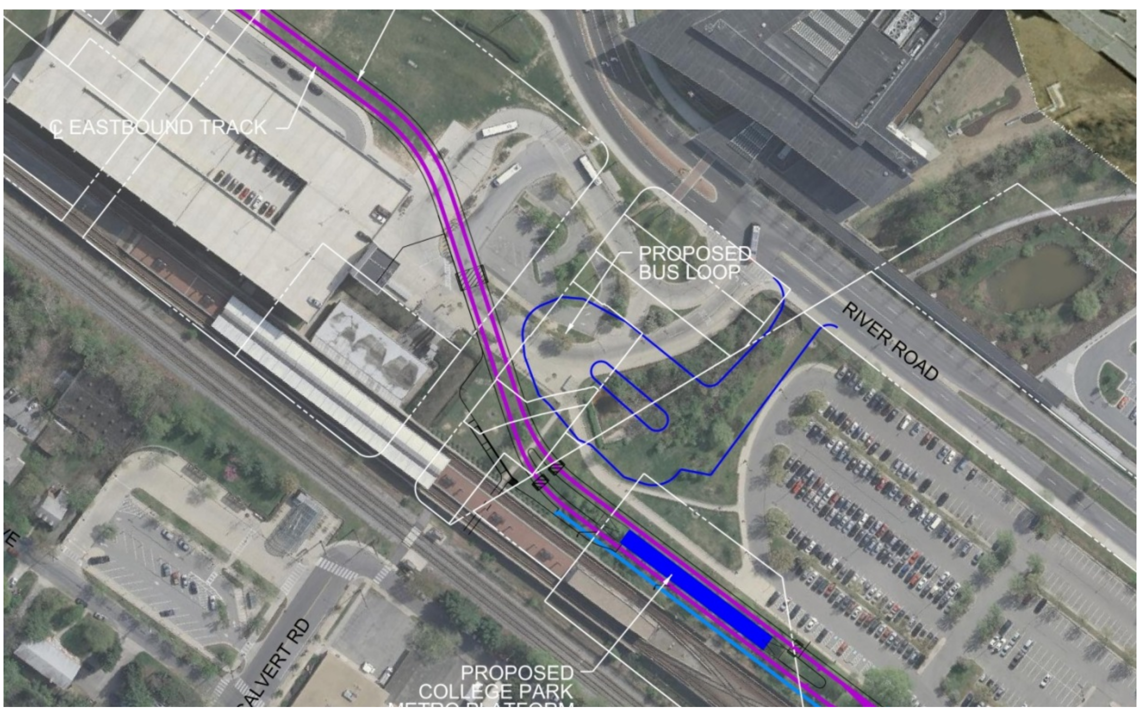

FIGURE 10 College Park Metro Station.

RIVERDALE PARK STATION: BYPASSING A CONGESTED INTERSECTION

Traveling from west to east the Purple Line will turn left from Kenilworth Avenue to MD 410 (Figure 11). Both of these roads are major regional arterials with large amounts of traffic. The left turn at the intersection would be challenging at grade, delaying transit travel times by 90 s. MTA evaluated use of an aerial alignment, weighing the cost versus the improved travel time and reliability. The local elected officials were supportive of the elevated structure, seeing it as an opportunity to revitalize the area and serve as an anchor for transit-oriented development surrounding the station area. This support, and the fact that the travel time savings and operational benefits were so beneficial, justified the cost.

ELLIN ROAD: UNANTICIPATED CONFLICTS

Some roads appear to present no design problems. Ellin Road is a four-lane road that is one of the approaches to the New Carrollton station. This station serves Amtrak's Northeast Corridor and the MARC commuter rail from Baltimore and points north, and it is the terminus of the Metrorail Orange Line. It is a busy transportation hub served by 24 bus routes. However, most users approach from the east side of the station and tracks; Ellin Road, on the west side, has low traffic levels, and the residential development bordering Ellin Road fronts internal neighborhood streets. Between the New Carrollton station and the neighborhood on the south side of Ellin Road is a large electrical substation. Early plans for the Purple Line located the trackway on this side of Ellin Road, parallel to, but outside of the road adjacent to the substation. As the designs progressed and MTA began coordination with the local electric company, MTA was informed of the fact that the proposed alignment would impact the underground electric grid that extended outside the substation.

FIGURE 11 Riverdale Park Station.

MTA was obliged to redesign the alignment to avoid impacting the grid. MTA worked with the local county's department of transportation to identify alternatives that did not require widening or any significant relocation of the roadway. The resulting design shifted a short segment of the roadway north near the substation in order to minimize impacts to the grid and constructed the light rail transitway within Ellin Road.

The selected alternative located the light rail in the outside lanes, where it will operate in mixed traffic. The eastbound lane, as it approaches the New Carrollton station, enters its own lane so that cars will not accidentally follow the train into the station.

For westbound Ellin Road traffic, the 13-ft outside lane will be shared use by the light rail and vehicles. The 11-ft right-turn lane at the intersection of Veterans Parkway and Ellin Road will be developed outside the shared-use lane. A second inside 11-ft through lane is designed to match existing conditions along the westbound direction of Ellin Road.

This alternative not only avoids the utility impact but narrows the transportation corridor, improving aesthetics and the pedestrian experience, reducing the number and height of retaining walls, and reducing forest and stream impacts. There were some disadvantages, chiefly that the light rail operations could be impacted by traffic, but they were determined to be minimal and therefore acceptable.

CONCLUSION

The Purple Line is a light rail line, with two-car trains, operating largely in exclusive or dedicated lanes. It has some extensive, and expensive, elevated features to avoid congested roadways. But it also includes segments that operate much like a streetcar in lanes shared with general traffic. These discrepancies are not a problem but rather are the result of conscious planning to design a system that is respectful of the existing conditions and future plans and the communities that it will serve. This is the core of successful insertion, building a light rail line in a developed corridor, working with the conditions that are found there.

State of Good Repair

San Francisco Municipal Transportation Agency's Twin Peaks Tunnel Trackway Improvement Project

CHUCK MORGANSON
RICHARD MARKS
NIKKI JEFFERY
HNTB Corporation

DAVID GREENAWAY
PRESTER WILSON
VINCE HARRIS
MATT LEE
TESS KAVANAGH
San Francisco Municipal Transportation Agency, California

The San Francisco Municipal Transportation Agency (SFMTA), California, has committed to investing $250 million annually over the next 20 years to improve the state of good repair. The Twin Peaks Tunnel Trackway Improvement Project is replacing 4 1/2 mi of worn light rail track along with systems and structural seismic upgrades within a tunnel built in 1918.

No alternative rail routes connect the neighborhoods served by the three SFMTA lines that travel through the Twin Peaks Tunnel to and from downtown. The SFMTA will maintain passenger service throughout the duration of construction by providing a bus bridge from downtown through to the terminal stations of each line in the western parts of the city.

This paper compares conceptual construction staging options developed that were based on the 1974 rail replacement and a final design study derived from recent experience with stages and production rates during non-revenue weekday–weekend work windows. The paper also provides the final agreement between engineering and transit operations on the allowable work hours and constraints on the contractor. A similar state of good repair track replacement project under construction in the nearby Sunset Tunnel provides lessons learned for the project. Stakeholder and public outreach strategy and execution are also examined.

INTRODUCTION AND BACKGROUND

The November 2014 election results in San Francisco showed clear public support for the SFMTA and the Municipal Railway (Muni) Metro light rail transit system that included a $500 million revenue bond for transportation improvements and a reaffirmation of the City's Transit First policy. Numerous state of good repair projects are planned in the years to come to upgrade the obsolete infrastructure that supports the movement of more than 700,000 daily trips on the seventh largest transit system in the United States. The SFMTA has committed to investing $250 million annually over the next 20 years to address an estimated backlog of $2.5 billion. The current 5-year Capital Improvement Program includes $1.5 billion dedicated to state of good repair investments (*1*).

One such project is the $41 million Twin Peaks Tunnel Trackway Improvement Project, which has been programmed and designed to replace 2 1/4 mi of light rail track within a closed tunnel environment, along with structural seismic and systems upgrades, all while maintaining passenger service throughout the duration of construction.

The existing track section was installed in 1974 with light rail vehicles powered by overhead catenary and a track section with ballasted 100-lb continuous welded running rail on creosote wood ties fastened to the rail with single-rib track plates attached with track spikes. The track was installed with a centralized traffic control (CTC) signaling system that includes insulated joints and impedance bonds. However, the track signaling is currently controlled by an advanced train control system (ATCS), which runs through the existing CTC signal relays. The selected replacement track section is ballasted 115-lb continuous welded running rail with Pandrol e-clip fasteners and Pandrol plates fastened to composite ties with lag screws. An existing No. 5 ballasted crossover on wood ties will be replaced with a No. 10 universal crossover, and an additional universal crossover will be installed. Embedded ballasted track at two underground stations within the tunnel are designated to be replaced with new concrete-embedded direct fixation track. Existing shoo-fly turnouts and tracks at the abandoned Eureka Valley Station will be replaced in kind and also used as an access point for construction.

Additional special track work includes the replacement of five embedded casting switches at the West Portal Half Grand and installation of new switch machines. Rail systems improvements and replacements include removal of the CTC signaling system, adding four new wayside track lubrication systems, replacing track switch machines, replacing undercar deluge systems at the one station, replacing gate valves for the firefighting stand pipe, installing a new fire alarm system at one station, cleaning out drainage lines, spot repairs of concrete spalls, and spot repairs to existing wood trim and doors. Seismic upgrade of an existing abandoned underground station includes adding additional columns and beams and strengthening of exterior walls (*2*).

Three Muni lines are served by the Twin Peaks Tunnel: K/T, L, and M. No alternative rail routes connect the neighborhoods served by these lines to their downtown San Francisco Metro connections. Muni will maintain passenger service by providing a bus bridge from downtown Market Street through to the terminal stations of each line in the western parts of the city during the regular revenue hours when service is affected by construction.

The nearby Sunset Tunnel serves the N line and has an ongoing track replacement project that has provided lessons learned to the Twin Peaks contract development (Figure 1).

CONSTRUCTION STAGING AND DURATIONS

The initial concept for construction staging sequence and duration was outlined in the Twin Peaks Tunnel Trackway Improvement Project Conceptual Engineering Report (CER) and was based on the agency’s experience of the rail replacement in the Twin Peaks Tunnel in 1974. It looked at three staging scenarios for disruption of revenue service for construction access: one long extended service shutdown, weekends only, and a combination of nights and weekends. The rail replacement production rate assumptions varied in the three scenarios from approximately 3,000 track feet per shift to 500 track feet per shift depending on the amount of mobilization and demobilization required (i.e., nightly shutdowns versus extended work hours and multiple sequential work shifts).

FIGURE 1 SFMTA Sunset and Twin Peaks Tunnels.

A further study conducted during the final design phase focused on the combination nights and weekends shutdown scenario. The study leveraged experience from recent tunnel track replacement projects for the Massachusetts Bay Transportation Authority in Boston and described likely durations of work breakdown stages on the basis of production rates during extended night non-revenue work windows and limited weekend shutdowns. The night work windows for the study were from 9 p.m. to 5 a.m., and weekend shutdowns were 56 h in duration (*3*).

The SFMTA's experience with the ongoing rail replacement project in the nearby Sunset Tunnel led the Capital Programs and Construction Division and the Transit Operations Division to agree that restricting the construction to weekend work only was the most likely route to a successful project. Important factors in this decision included community impacts and maintaining regular revenue service for the weekday commute.

The weekend work windows are planned to start at 10 p.m. on Fridays and will be concluded by 9 p.m. on Sundays. A total of 21 such weekends are allowed in the contract. There is a financial incentive for completion in fewer than the allowed number of weekends. No mechanism is planned for the contractor to request additional weekends. Liquidated damages and penalties will be assessed if the contractor cannot complete the scope of work within the allotted work windows.

In addition to the weekend work, it is expected that the contractor will perform daytime weekday work in designated staging areas outside of the tunnel. These activities include delivery and welding of rail, pre-plating ties, unloading and disposal of materials and equipment from the previous weekend's work, and staging of equipment and materials for the next weekend's activity. There is also potential to perform some of the seismic retrofit work during the daytime. The normal day shift work would be limited to areas that have greater clearance from the main-line revenue tracks. In order to perform this work during normal day shift hours, a protective wall of plywood would be placed to prevent the tracks from being fouled. Concrete and shotcrete deliveries during normal day shift working hours do not require overtime or plant opening costs for the ready mix supplier which would otherwise significantly increase the cost of the concrete.

Ongoing systems improvement contracts to replace emergency blue-light telephones and install equipment for an agencywide radio replacement project will also need to perform work within the Twin Peaks Tunnel. These contracts are planned to complete their scope of work within the Twin Peaks Tunnel before the track replacement project begins construction (Figure 2).

The CER and the final design study examined different scenarios for accomplishing the work within the Twin Peaks Tunnel. The final contract plan was informed by these studies and the planned versus actual production rates for the Sunset Tunnel project (Table 1).

TWIN PEAKS: FINAL DESIGN STUDY, POTENTIAL SEQUENCE OF WORK

Detailed work plans for open tunnel, divided tunnel, special trackwork, and seismic retrofit work were developed during the final design phase study. The work plans detailed the typical night and day shifts assumed in the study (Table 2).

The work plans provided information on required personnel and types of equipment, tools, and materials required to complete the scope of work (Table 3). The plans further detailed the work schedule breakdown during a typical night closure in 13 work activity steps (Table 4 and Figures 3 through 9).

Typical Night Closure Work Activity, Steps 1–13

1. Safety talk and prep time, 9:00–9:30 p.m.:
   – Safety talk to inform personnel of the nights work schedule, train service movement, equipment routing, and so forth.

FIGURE 2 Contract timeline.

TABLE 1 Comparison of Production Rates and Work Windows

	Tunnel Work Duration	Rail Replacement Production Rates (per shift)	Seismic Retrofit	Approximate Total Tunnel Work Hours	Comments
TWIN PEAKS TUNNEL: 22,800 TF Total Track Replacement					
CER: complete shutdown	4 weeks	1,280 TF	35 days	600	Complete shutdown assumed to be 24- h work days, 6 days a week. Seismic retrofit work assumed to be 2 x 8 h shifts per day.
CER: weekend shutdowns	10 weekends	2,880 TF	12 weekends	700	Weekend shutdown assumed to be 56 h from Friday 9 p.m. to Monday at 5 a.m. Seismic retrofit can be done concurrently with rail replacement.
CER: nightly shutdown	50 nights and 2 weekends	480 TF	12 weekends	1,000	9 p.m. to 5 a.m., 5 days a week
Final design study	230 nights and 13 weekends	156 TF open tunnel 78 TF divided tunnel	90 nights and 5 weekends; some work concurrent with rail replacement	2,500	Nightly and weekends shutdown hours assumed to be the same as the CER. Seismic retrofit can be done concurrently with rail replacement.
Final contract plan	21 weekends	1,080 TF	Concurrent with rail replacement	1,000	Weekend shutdown assumed to be 47 hours from Friday 10 p.m. to Sunday 9 p.m.
SUNSET TUNNEL: 9,500 TF Total Track Replacement					
Assumed in contract	15 weekends	1,000 to 1,200 TF	Some structural and systems work concurrent with rail replacement	860	10 weekends planned for rail replacement, 5 for structures and auxiliary work. Weekend shutdown planned to be 57 h from Friday 8 p.m. to Monday 5 a.m.
Actual production rate	14 weekends +1 non-production weekend	800 TF	Some structural and systems work concurrent with rail replacement	TBD	12 weekends actual to complete rail replacement, 2 additional available for auxiliary work. Actual weekend Friday 10 p.m. to Sunday 9 p.m.

NOTE: TF = track feet; TBD = to be determined.

TABLE 2 Work Shifts

Shift	Day	9 p.m.	10	11	12 a.m.	1	2	3	4	5–7	8	9	10	11	12 p.m.	1	2	3 p.m.
1	Sun.																	
2	Mon.																	
3	Tues.																	
4	Wed.																	
5	Thurs.																	
6	Fri.																	
7	Sat.																	

Night Shift (9 p.m.–5 a.m.)

Day Shift (8 a.m.–4 p.m.)

- Prep time:
  - Starting equipment,
  - Checking material for nights work, and
  - Authority coordinator and contractor supervisor to process right-of-way (ROW) documents and train orders for equipment movement and power deenergizing process.

2. Power deenergizing and diversion set-up, 9:00 to 10:00.p.m.:
   - Authority coordinator, contractor supervisor, and power lineman after last train and receiving permission from power dispatcher and central control for lockout and tagout of the diversion section and test and install safety warning devices;
   - Authority coordinator and contractor supervisor to confirm warning devices are set in place to protect diversion area; and
   - Contractor electricians' removal of ATCS signal cable.
3. Personnel, equipment, and material to enter tunnel from Eureka staging area, 9:30 to 10:00 p.m.:
   - Hi-Rail crew cab pickup to go out first on working track.
   - Via-Car with two work flats loaded with material out second on working track.
   - Gradall out third on working track.
   - Three dump trucks enter from West Portal fourth, fifth, and sixth on opposite track facing forward.
   - Unimog with two empty work flats out seventh on opposite track being worked on.
4. Remove joint bars and cut track into 13-ft panels, 9:30 to 10:30 p.m.:
   - Remove cables from around joint bars and relocate to 156-ft cut-in location.
   - Two laborers to remove compromise joint bars and relocate to 156-ft cut-in location.
   - Contractor's foreperson measures and marks 13-ft sections of old track to be saw cut into panel sections.
   - Four track persons with two rail saws cut 100-lb rail into 12- to-13-ft panels of old track.
5. Remove 13-ft panels of old track and load to flat cars, 9:30 to 10:30 p.m.:
   - Gradall with transfer bar chained to bucket.
   - Gradall will grab wheels and leave rail to ballast toward the track dummy (the area between the inbound and outbound tracks).
   - Gradall with rubber tires on ballast will position transfer bar at center of 13-ft old track panel and connect rail tongs to head of rail.
   - Gradall will lift 13-ft old track panels to opposite track on which Unimog is positioned to receive onto work flats. Gradall will continue this process from ballast until all 12- to-13-ft old track panels are on work flats.
   - Unimog with flats loaded with 12- to 13-ft old track panels returns to staging area.
6. Remove old ballast, 10:30 p.m. to 12:30 a.m.
   - Gradall will start excavating the track.
   - Dump truck toward West Portal will load first. Full dump truck will proceed west to parking lot staging area to unload. Empty dump truck will proceed back to opposite track to be loaded.
   - Gradall will continue loading each dump truck until ballast is removed.
   - Last Hi-Rail dump trucks will exit track at West Portal.
   - Gradall will re-rail from ballast to running rails.

TABLE 3 Personnel, Materials, and Equipment

Personnel		Materials	Heavy Equipment			Small Tools		Specialty Equipment
Authority	Contractor		Fixed Rail	Hi-Rail	Construction	Power Tools	Hand Tools	
Project manager (day and night)	Project manager	Compromise joint bars	Production tamper	Hi-Rail crew cab pickup	Front end loader	Gas-powered rail saw	2 track wrenches	Rail tongs
Coordinator (day and night)	Track construction supervisor (day and night)	Oval neck joint bolts	4 work flats	Gradall	Trailer flat	Saw blades	4 track hammers	Transfer beam with 2 pairs rail tongs
Power person	3 track forepersons (1 day, 2 night)	Split washers	4 ballast cars	ViaCar	Tractor	Gasoline for 2- and 4-cycle equipment	2 sets of tie tongs	2 sets of rail tongs
Track construction engineer (day and night)	8 equipment operators (1 day, 7 night)	115-lb joint bars	Spot tamper	Unimog		Gas-powered rail drill	4 lining bars	2–10 ft chain
2 flaggers	2 electricians (signals)	2–39 ft 115RE rail joint hole drilling both ends		4 Hi-Rail dump trucks		1-1/16 in. drill bits	2 track punches	Diesel fuel
Signal person	Track construction engineer (day and night)	19 preplated 7 ft x 9 ft x 8 ft 6-in. ties with Pandrol plates fasteners				Rail grinder	2 track chisels	Re-railing equipment
	10 track laborers (3 day, 7 night)	76 Pandrol e-clips.				Generator	6 ballast forks	Alignment and profile leveling equipment
	Master mechanic (day and night)	8 Pandrol J clips					Track masters gage	Cembre fastener tools
		Ballast						
		12–48 in. 500 concentric cable with Cembre lug connectors both ends						

TABLE 4 Typical Night Closure: 13 Work Activity Steps

9.p.m.													
9:30													
10:00													
10:30													
11:00													
11:30													
12:00													
12:30													
1:00													
1:30													
2:00													
2:30													
3:00													
3:30													
4:00													
4:30													
5:00													
Shift end time													
Work steps	(1) Safety talk and prep time.	(2) Power de-energizing and diversion set-up. Remove ATCS signal cable.	(3) Equip-ment and material enter ROW, crews travel to tunnel work site.	(4) Remove joint bars and cut track into 13-ft panels.	(5) Remove 13-ft track panels and load to flat cars.	(6) Remove old ballast.	(7) Lay out preplated ties.	(8) Install 39-ft rails with joint bars and clip rails to ties.	(9) Position track jacks to set horizon-tal and vertical align-ment.	(10) Unload new ballast.	(11) Ballast tamping.	(12) Install and splice ATCS signal cable and surface ballast.	(13) Inspect track, remove diversion equip-ment, restore power.

FIGURE 3 Mobilization of Hi-Rail equipment and removal of old rail and ties.

FIGURE 4 Removal of old rail and ties.

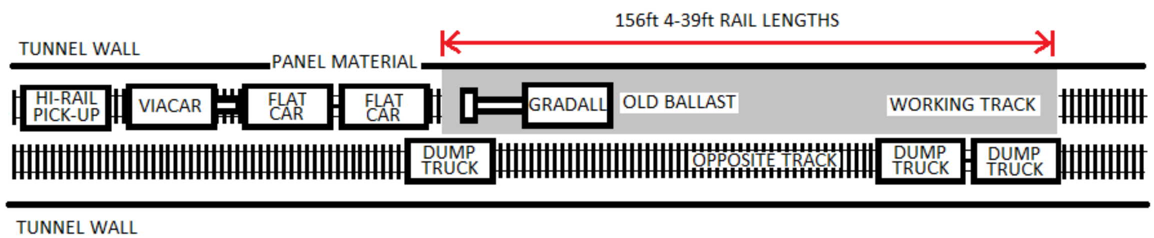

FIGURE 5 Removal of old ballast.

7. Lay out preplated ties, 11:30 p.m. –1:00 a.m.:
   – Gradall will remove from work flats 12 bundles to excavate track between filling dump trucks.
   – Laborers and track persons with tie tongs will lay out preplated ties.
   – Gradall will continue loading dump trucks.
   – Pickup and ViaCar with remaining panel material will cross over to opposite track after last dump truck is loaded.
   – ViaCar on opposite track will unload remaining bundles of preplated ties to excavated track. Laborers and track persons will lay out preplated ties.

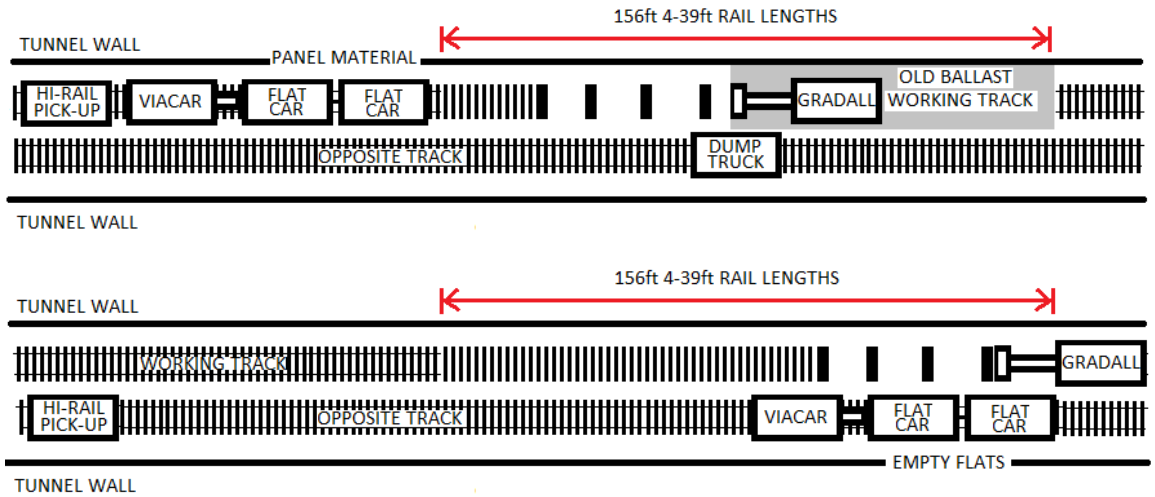

FIGURE 6 Removal of old ballast and installation of preplated ties.

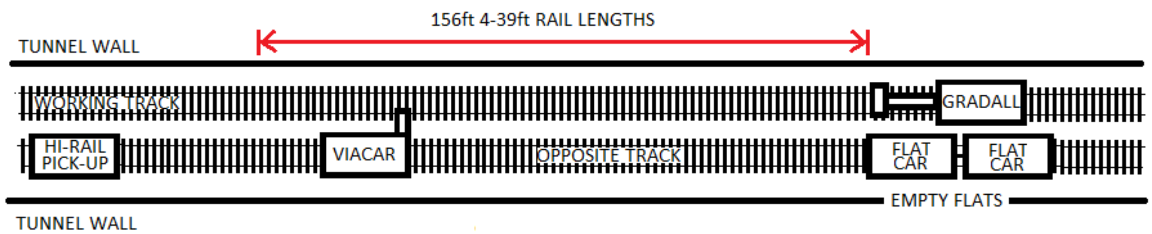

FIGURE 7 Installation of running rail.

8. Install new 115-lb rails with joint bars, 12:30 p.m. to 2:00 a.m.:
   – Gradall and ViaCar to install 156 ft of 115-lb rail with grab chain and rail tongs. Rails will be unloaded before track construction along the ROW between rails and dummy.
   – Laborers to install joint bars.
   – Track persons to install compromise joint bars. Existing rail could have vertical or horizontal wear that will create a mismatch. A 5-ft 100-lb compromise rail will be used as needed.
9. Position track jacks to set horizontal and vertical alignment, 1:00 to 2:00 a.m.:
   – Gradall will return to Eureka staging area.
   – Laborers will set track jacks every fifth tie on both ends of the same tie. Track jack will be used to set alignment.
   – Construction supervisor and authority engineer will set top of running rail to existing alignment and profile with alignment and leveling equipment.
10. Unload ballast, 2:00 to 3:00 a.m.:

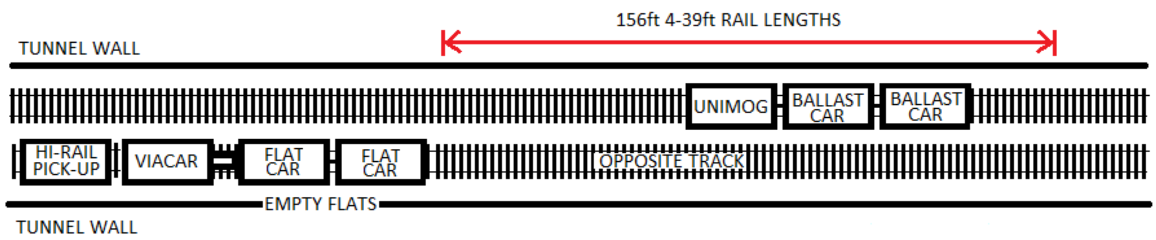

FIGURE 8 Surface, line of track, and unloading ballast.

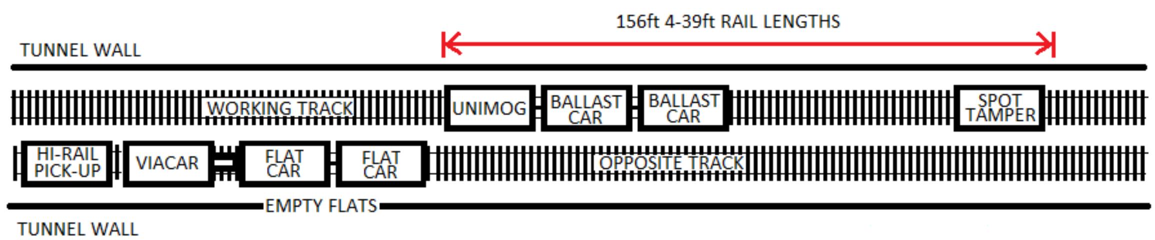

FIGURE 9 Unloading ballast and tamping ties.

– Unimog will unload old track panels and load material for next construction night. Hoist truck with trailer will work from street. Unimog will then attach to four loaded ballast cars and proceed to working track.

– Construction foreperson will unload ballast from doors beneath the cars to just below top of rail.

– Unimog with empty ballast cars will return to Eureka staging area to fill ballast cars and return to working rail to unload ballast.

– Unimog and ballast cars will return to Eureka staging area to layup.

11. Tamping, 3:00 to 4:00 a.m.

– Spot tamper will follow Unimog and reloaded ballast cars to working track.

– Spot tamper will cycle heads four times up and down on each tie.

– Construction supervisor and authority engineer will confirm proper track profile and alignment.

– Spot tamper will then return to Eureka staging area.

12. Install signal cables and surface ballast, 3:30 to 4:30 a.m.

– Contractor's electricians will install ATCS signal cables at rail joints and running rails as needed. Cembre connections on cable will be needed.

– Laborers will surface ballast from top of ties and under running rails.

– Track persons will load tools and equipment to ViaCar with work flats, and Hi-Rail pickup will return to Eureka staging area.

13. Inspect track, remove diversion equipment, and restore power, 4:30 to 5:00 a.m.;

– Construction supervisor and authority engineer will inspect panel construction. Construction inspection form will be used and signed off.

– Construction foreman and authority coordinator will remove diversion equipment and secure equipment and personnel from staging area.

– Construction supervisor, project coordinator, and power lineperson will restore power.
– Test train will run entire diversion area.

SUNSET TUNNEL TRACK REPLACEMENT PROJECT: LESSONS LEARNED

A similar track replacement project in the Sunset Tunnel, which serves the N line, provided lessons learned for the agency.

The Sunset Tunnel track replacement project experienced community opposition primarily because of the night noise impacts of the equipment backup beepers and ballast delivery and handling. In San Francisco, when a protest is filed at the board of appeals for night work permits, the permit is automatically suspended until a hearing is completed. An expedited hearing was scheduled for the Sunset Tunnel project that resulted in an 8-week delay to the contract.

The night noise mitigations that were added to the reissued permit include the following:

- Ballast delivery is restricted to 6:00 a.m. to 9:59 p.m. on Fridays, Saturdays, and Sundays.
- Ballast may be loaded into the ballast cars at night, but additional sound dampening is required to be added to the ballast cars.
- Mufflers are required on all construction equipment.
- Install and utilizing the broadband (white noise) backup alarms on all equipment is required.
- If the residents adjacent to the construction site object to the sound of the replacement broadband backup alarms, discontinue use and implement other backup warnings approved by the Occupational Safety and Health Administration, such as flashers or flag persons, or both.
- Continuous automatic noise monitoring and recording near property lines is required.
- Impact tools must be equipped with intake and exhaust mufflers.
- Pavement breakers and jackhammers must be equipped with attenuating shields or shrouds.
- Electric equipment shall be used over diesel powered whenever possible.
- Generators and compressors shall be acoustically shrouded or shielded.

Multiple work weekends have been performed successfully with these mitigation measures in place without additional formal complaints. These provisions are now included in the Twin Peaks contract requirements. In addition, drainage line video inspection has been added to the Twin Peaks scope because of the experience of similar drains in the Sunset Tunnel. In general, the new permit conditions are working well for the Sunset Tunnel project (Figure 10).

FIGURE 10 Sunset Tunnel construction.

STAKEHOLDER AND PUBLIC OUTREACH

The major areas of construction impacts are night noise, contractor laydown areas, rail welding staging areas, ballast import and off-haul, rails and railroad tie delivery, and modified passenger service.

The SFMTA outreach team will employ a similar strategy for Twin Peaks as it has for Sunset Tunnel, which includes the following measures from the agency and the contractor:

- E-mail and public flyer notification on the project website and prominent public spaces,
- Notification of bus bridge pickup and drop-off locations,
- Use of multiple construction crews to advance work as quickly as possible,
- Traffic control officers to maintain traffic flow and ensure local access,
- SFMTA ambassadors to advise customers about substitute bus service, and
- Informational signage that directs customers to transfer points between rail and bus service and advises customers that businesses are open and accessible during construction.

Figure 11 shows a typical Sunset Tunnel public notification.

Service alerts along the routes provide notices of changes to service in English, Chinese, and Spanish and include duration of impacts and locations of temporary bus shuttle stops (Figure 12).

As part of the Sunset Tunnel Trackway Improvement Project, the SFMTA will continue the weekend construction on the Sunset Tunnel on April 10-13. By replacing the aging track and other infrastructure inside the Sunset Tunnel, the project will help improve safety and reliability of the N Judah rail service for Muni customers.

Seismic upgrades to Sunset Tunnel are an important part of the safety enhancement project. It will involve structural retrofit of the tunnel portal retaining walls and their foundations.

During construction, the SFMTA will continue to implement the work plan to better control the night time noise. Noise mitigation measures will include:

- Using both west and east portals for removal and handling gravel ballast;
- Delivering gravel ballast to the job site only between 6 a.m. and 10 p.m. Fridays through Sundays;
- Installing mufflers on the construction equipment and using acoustically attenuating shields or shrouds on impact tools;
- Using new backup alarms with lower noise level; and
- Using electric powered rather than diesel-powered equipment whenever possible.

The Sunset Tunnel construction is scheduled to take place on 15 weekends between November 2014 and fall of 2015.

What to Expect during Weekend Construction:

- Crews will work continuously from approximately 8 p.m. on Friday until 5 a.m. on Monday.
- The majority of the work will take place inside the Sunset Tunnel and at the tunnel entrances.
- Noise control measures will be implemented; however the work will be audible throughout the weekend.
- The streets near the tunnel entrances will remain open.
- To accommodate the tunnel work, parking restrictions will become effective from Friday 12 a.m. to Monday 5 a.m. on both sides of Duboce Avenue from Steiner to Scott Street, and on both sides of Carl Street from Clayton to Cole Street.

Weekend Bus Substitution Service:

- Bus shuttles will substitute for the N Judah rail service between Church & Duboce and Ocean Beach.
- Bus substitution will start at about 7 p.m. on Friday and will be operated during regular service hours until early Monday morning
- The bus shuttles will follow the N Judah Line making regular stops except for the tunnel portion where buses will be routed to Haight Street.
- Regular N rail cars will continue to provide service between Caltrain Depot and Church & Duboce.
- The N Judah stops at Church & Duboce will provide a transfer point between bus shuttles and trains for Muni customers.
- The weekend N Judah Owl bus service will not be affected.

The Transit Signal Priority (TSP) system upgrades are taking place at nine intersections sequentially along the N Judah Line. The TSP system will use technology to reduce dwell time at traffic signals for Muni light rail vehicles by holding green lights longer.

Thank you for your understanding and patience while we work to improve your Muni system.

FIGURE 11 Sunset Tunnel public notification.

FIGURE 12 Bus bridge notification sign.

CONCLUSION

The lessons learned from the Sunset Tunnel track replacement project about noise mitigation and public information have strengthened the Twin Peaks project. As the voters and traveling public of San Francisco experience the successful implementation of the two trackway improvement projects, they will understand that the SFMTA is wisely investing the funds entrusted to it through enhanced system reliability and efficiency, reduced maintenance delays, and improved seismic safety.

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LRT in the Total Transit System

Light Rail Hubs in a Multimodal Transport Environment

MARTIN SMOLINER
STEFAN WALTER
MARTIN FELLENDORF
Graz University of Technology

In an increasingly multimodal urban transportation environment, not only route design and system insertion of light rail systems alone, but also the design of multimodal hubs, are of crucial importance. The integrated design of light rail infrastructure and other modes of transport always need to be tackled on a networkwide scale to gain a maximum network effect.

In this paper the most important success factors are identified by evaluating classical planning strategies found in the literature. This shows that there are several very basic yet crucial success factors. An integrated management and planning framework is essential for achieving an integrated multimodal transportation network. Timetable-oriented network design together with attractive transfer conditions for passengers have also proved to be important. One factor is the location of a hub that needs to align with urban subcenters, so local demand attractors form synergies with passengers transferring at the hub. When designing the hub itself visibility, accessibility, and safety as well as security and comfort aspects need to be considered. The methodology contains a 3-stage framework to integrate light rail within a transit system via hubs. A multimodal, activity-based travel demand model; timetable design; and route network design affecting track, platform, and station geometry are described. Only a tight integration of travel demand modelling, urban planning, operating, and design of public transport as well as road infrastructure planning can lead to the successful establishment of multimodal hubs. Quantitative and qualitative performance indicators are given for various hubs in central Europe to analyze their performance.

INTRODUCTION

Relevance

In recent years public transportation systems around world have seen an increase in ridership, notably due to rising gasoline prices and steady urban growth. This is particularly true in North America, where transit use in 2006 reached its highest in the past five decades (*1*).

In the course of this development, the United States and other regions in the world are seeing a comeback of light rail systems. From only 8 light rail systems in the United States in 1977 (*2*), this number has risen to 33 systems in 2014 (*3*), showing that light rail transit (LRT) has been established as an attractive addition to local transit systems (*2*).

Transfer hubs are the key nodes of the transit network. Besides (intermodal) changes of vehicles, hubs play a very important role in cutting down passenger travel time (including waiting time and transfer time) (*1, 2*). Hubs also help to redistribute and evenly spread passengers. As intercity travel is expanding as well as traffic within metropolitan areas, multimodal hubs are becoming ever more important. In addition, existing transit networks and stations need to be redesigned due to significantly higher volumes of passengers (*4*).

The literature has shown that passengers put severe transfer penalties on connections that include transfers (*5*). Transfers cause additional cognitive effort on the part of passengers, a factor which reduces the attractiveness of public transport (*6*). Furthermore, Brons et al. have shown that measures associated with the convenience or ease of rail travel, including better access, might provide greater benefits for rail users (*7*). Improving accessibility of railway stations, whether by car or public transport, is likely to improve rail use and public transport use in general.

In an increasingly multimodal urban transportation environment, not only route design and system insertion of light rail systems alone, but also the design of multimodal hubs, concentrating especially on the passenger flows, are thus of crucial importance. The integrated design of light rail infrastructure and other modes of transport always need to be tackled on a larger, networkwide scale to gain a maximum network effect.

Definition of Multimodal Hub

APTA defines "intermodal" as "Those issues or activities which involve or affect more than one mode of transportation, including transportation connections, choices, cooperation and coordination of various modes. Also known as 'multimodal'" (*8*). According to Saxena and Liu a multimodal hub or interchange can be defined as "A place where passengers change transport modes e.g. train stations, mass rapid transit stations, bus stops, airports" (*9*). The *Transit Capacity and Quality of Service Manual* defines "intermodal terminals" as "Transit center - a transit stop or station at the meeting point of several routes or lines or of different modes of transportation. It is located on or off the street and is designed to handle the movement of transit units (vehicles or trains) and the boarding, alighting, and transferring of passengers between routes or lines (in which case it is also known as a transfer center) or different modes (also known as a modal interchange center, intermodal transfer facility or an hub)" (*10*).

In this paper, hubs will be covered that are connected to a light rail system and at least four bus lines.

Naming Conventions

In this paper, a "hub" denotes the entirety of a multimodal transfer station with all the facilities connected to it. A "station area" shall denote a part of the hub devoted to one mode of transport, be it rail, LRT, bus, parking, or others. A "platform" is the physical structure of a public transport stop used for boarding and alighting. A "berth" shall denote the space for one vehicle along a platform as well as the area used for boarding and alighting kiss-and-ride customers. "Amenities" shall subsume all facilities not directly needed for the operation of the hub, such as kiosks, information counters, or sanitary facilities.

OBJECTIVES

The objectives of this paper are to analyze success factors for multimodal hub design and find a catalogue of key factors for the successful integration of a light rail system within the total transport system. This way an interdisciplinary, multimodal, highly iterative and long-term design methodology for light rail extensions is provided within a total transit system. Finally, this paper analyzes some best and worst practice examples by applying the presented methodology.

LITERATURE REVIEW

The literature dealing with the design of multimodal transport hubs can be divided into three main topics: Theoretical network approaches discuss the allocation of hubs, methodologies evaluate the design process of recently built or planned projects and finally existing hubs are analyzed to derive key success factors.

Common systematic engineering methods for solving public transit network optimization for instance are genetic algorithm, ant-colony algorithm, optimization theory, and graph theory (*11*). Ravulaparthy and Goulias apply graph-theoretic approaches to identify major centers and subcenters (*12*). Highly central location shows a strong interdependence of transportation networks along with their geometry in spatial patterns and locational activities. Derrible uses the theory of centrality and the measures of degree, closeness, and betweenness centrality to evaluate the relationship between transport and land use, based on data about geometric structure to determine key transfer stations in public transport networks (*13*). Wang and Chen applied the hub and spoke theory in combination with a hybrid network to combine a grid structure in the city center with a hub and spoke pattern in the periphery (*1*, *11*). Roca-Riu et al. suggest the hub and spoke theory for planning freight networks (*4*). An extensive state-of-the-art overview regarding hub and spoke networks is presented by Alumur and Bahar (*14*). Ceder and Chowdhury assume that there is a transfer penalty in the minds of public transport users for routes with interchanges (*5*). In common with other researchers they use the theory of planned behavior to explore perceived behavior control and to take a more psychological approach to understanding the willingness of passengers for using public transport hubs.

Metrolinx provides a detailed guideline for defining a mobility hub, for questions of placement and successful implementation of multimodal hubs (*15*). Nagorsky published a 7-step methodology for locating and designing access planning of commuter rail (*16*). Transport for London published a quick reference guide on interchange best practice cases covering a design and evaluation framework evaluating criteria concerning the efficiency, usability, understanding and quality of hub infrastructure (*17*). Saxena and Liu present an evaluation framework based on stakeholder requirements for multimodal passenger hubs in China (*9*). Aspects of hub design on a more specific level are covered by Bendfeldt, who deals with standardization possibilities of track layout in rail hubs (*18*).

Keller, Tsavachidis and Hecht point out key issues for seamless travelling through interconnections (*19*). They cover Trans-European, regional, and local networks and provide best practice cases while Becker (*20*) analyzes quality and design of several stations within a regional rail network.

ANALYSIS OF KEY FACTORS

Crucial key factors toward designing a successful transport hub cover a wide range of issues, extending from the comprehensive general design framework down to the design of individual walkways. These are discussed first to allow for a classification. The derived key factors should be essential regardless if new ones are planned from scratch or existing hubs are discussed.

Classification

Public Transport Alliances

Transport alliances are usually referred to as one common organizational unit that combines several transit operators. This includes a one-stop-shop approach: one fare structure with single tickets for various operators and single journey planners. Nevertheless operators stay individual economic business units.

In a multimodal transport system, transport alliances go much further than applying a combined fare system. In addition to an agreement on the application of a common fare and through ticketing, they allow for a transport-level cooperation, a coordinated organization of the network and timetable as well as a general management of the transport system as a whole (*21*). The success of multimodal hubs thus starts as early as public transport alliances. All actors, representing different transportation modes and transit companies, start a common planning process in order to reach a well-designed hub (*20*). Harmonized schedules of all modes available at the interchange guarantee short transfer and waiting times, furthermore a transport alliance allows for a flexible, multimodal handling of any system interruptions consisting of information, substitute services, additional individual support, and reimbursement (*19*).

Urban Development Plan

The allocation of a multimodal hub should align with the urban development plan and be situated at major points of interest or local centers within an urban or metropolitan area. District centers should always function as hubs, so that radial and tangential lines can be coordinated for good connections between urban centers and a subcenter. Bundling public transport and consequently enabling centralized transfers in these local centers facilitate the coordination of different lines. Hubs offer high-quality accessibility to public transport and allow a connection to other high-grade modes of transport. Urban development should concentrate (utility) services around hubs to create and strengthen subcenters within the urban area. In addition, monocentric urban layout structures should be transformed into a polycentric and clustered structure in order to disperse the traffic demand in the urban central district (*11*). In the long run, spatial distribution of the population can be controlled by the location of multimodal hubs and their supply of public transport (*7*).

Route Network

A public transport network needs different transit line levels in order to meet the different trip distances, speeds, and passenger volumes (*11*). The hub and spoke network structure offers a solution for a multilevel transit network and the planning of multiclass transfer hub locations (*11*). This network structure can increase the operation efficiency and achieve maximum transit benefits as it allows consolidate flow and takes advantage of economies of scale. Alternatively a hybrid network that combines a grid structure in the city center with a hub and spoke pattern in the periphery fits metropolitan structures best.

Location of Hub

Public transport hubs, especially when designed as intermodal hubs, need to interact significantly with their surroundings if they are to draw a maximum use of shared amenities. It is therefore desirable to locate these hubs either directly at or in the immediate proximity of urban centers. First, it is more economic to make shared use of amenities existent in either facility (shops, sanitary facilities, information counters). Second, public transport riders can spend time during transfers within an attractive urban environment. And third, the urban center will profit from additional customers. In addition, a transfer hub should be located at the point that is serving the maximum number of people and jobs within a reasonable walking distance (*11*). According to Saxena and Liu, a hub location in the center (or a subcenter) is preferable to an allocation on the outskirts of a city (*9*).

The network layout and thus the location of transfer hubs heavily depends on whether strong trunk lines in a hub and spoke network prevail over parallel lines with more direct services, whether the network trends to cover a larger area with more lines or rather a denser service on fewer high-performance corridors, and whether the individual intervals are coordinated to form intended transfer meetings or rather follow individual service patterns with immediate passing of transfer stations and thus longer transfer times. Daganzo recommends that hub locations are determined where stop spacing, service frequency, and appropriate line spacing best balance the general user cost with the cost of providing the service (*22*). Location of hubs can be defined by cluster-based hierarchical location models with the objective of minimizing total travel time (*11*).

Multimodal hubs emit and attract a significant volume of personal motor vehicle traffic, with the result that the position of these within the named networks needs to be carefully designed to allow for both adequate accessibility and sufficient capacity, while minimizing the impact of automobile traffic from access and egress of the urban center itself.

Timetable Coordination

Harmonized schedules ensure the coordination and connectivity for both intermodal and intramodal transfers (*5*). For lines with intervals greater than 20 to 30 minutes, the clock-faced schedule allows for an integrated timetable for all lines to be incorporated. Shorter intervals require a periodic timetable optimization approach (*23*, *24*). Ceder defines a well-connected transit path as “an advanced, attractive transit system that operates reliably and relatively rapidly, with smooth (ease of) synchronized transfers, part of the door-to-door passenger chain” (*25*, *26*). According to Ceder and Chowdhury, missing a connection while making a transfer often substantially negatively affects quantitative attributes such as travel time and waiting time as well as qualitative attributes such as anxiety, comfort, and safety (*5*). Unreliability of service is, apart from safety, the key factor for improving traffic at hubs and increasing passenger flow/numbers (*5*). Furthermore, journey time and waiting time have been identified as the most sensitive performance indicators (*27*, *28*). Initial waiting time has shown to be more onerous than in-vehicle time and interchange waiting time (*25*); perceived waiting time is much more onerous than actual waiting time. Ceder and Chowdhury show that the maximum accepted interchange time (walking and waiting time) is 5–10 min (*5*).

Track Layout

Track layout is predominantly determined by timetable and frequency of lines to be connected at a hub. This affects the arrangement of tracks and platforms already from the start, since the clock-face schedule in particular requires considerable planning efforts for hub track layouts. In following a strict form-follows-function approach, it is crucial to construct a track layout that follows the timetable requirements and not vice versa. However, besides designing planned conditions, accidents, failures, or special events causing different stopping patterns and requiring additional tracks need to be considered (*29*). Zwaneveld et al. (*30*) and Bendtfeldt (*18*) present planning principles and methodologies for designing track layouts.

Model

Travel Demand Model

Nagorsky underlines the need for a robust and extensive evidence base beyond ridership forecasts and documentation of existing needs (*16*). A detailed demand model gives stakeholders confidence in the recommendations and facilitates a well-founded planning process. A well-kept and calibrated multimodal travel demand model capable of modeling modal shift and sensitive to timetable changes is required. For intermodal hubs, especially, a fine-grained passenger flow simulation capability is required. The traffic model must be capable of modeling the very effect of footpaths on the total travel time. For brevity reasons, this paper can only roughly outline the requirements of the demand modeling process; refer to Fellendorf et al. (*31*), Friedrich et al. (*32*), and Walter and Fellendorf (*33*) for further details on this issue.

The creation and calibration of the demand model as well as the quality of the input data are crucial for the quality of the whole design process. Therefore at this stage, trade-offs between project speed (or workload) and demand modeling pose a serious risk to the quality of the whole process. The demand model plays an important role throughout and will be fed with new information in several project stages in order to produce new input data for the other fields of design.

Design

Hub Infrastructure Design

Past research on access to railway stations, multimodal public transport, and transfer inconvenience indicates that the accessibility of a hub is an important factor for mode choice (*34*). Level and quality of the access to the station is an important dimension of the rail journey, influencing the overall journey satisfaction. Improving and expanding access services to the railway station can cost-efficiently substitute measures on the rail network (*7*).

For a smooth transfer, short connections within a hub are essential. Stairs, escalators, and elevators are needed to provide comfort and speed (*19*). Surprisingly, in a survey in Graz, Austria, climbing stairs was not a disturbing factor for 80% of passengers using urban hubs.

Visibility plays a vital role in designing hubs, since a direct view between main destinations—platforms, entrances and exits—improves safety and orientation (*19*). Orientation when leaving vehicles, station overview, and orientation within a station should be self-explanatory and intuitive (*7*).

Furthermore accessibility for persons with reduced mobility is absolutely crucial and needs to be guaranteed through attractive design that is free of barriers and will be the main focus in redesigning stations in the future (*19*, *20*).

Information

Transfer information is a substantial interchange attribute to passengers (*5*). This often includes multilingual signage throughout the station, real time on-screen information that is easy to read and understand, and speakers not only in the hub but also in vehicles (*7*, *19*). This is especially important in larger cities or tourist areas. Furthermore, signage displaying time gap for transfers as well as combined static and dynamic data on public and private modes (trip planning systems) should be provided (*19*). Advanced information is an especially important requirement wherever there is a high percentage of nonfrequent traffic or in the case of any special circumstances (events, accidents, or construction works) to give advice about alternative routes (*4*, *5*, *18*, *20*). A lack of information is placing big penalties for routes with transfers, especially if passengers switch to modes or vehicles with lower frequency. Furthermore if travelers feel in control of their journey their willingness to use routes with transfers increases (*5*).

Walking Distance and Time

Walking distances should be generally kept as short as possible, especially for transfers, and may be longer toward the exit, since transfer walking has shown to be more onerous than exit or entry walking (*5*, *19*). Walking escalators, longer ramps, and level interchanges have a positive effect on transfer attractiveness (*5*). The splitting of boarding and alighting passengers is necessary at heavily frequented platforms. Street crossings (without traffic lights) for accessing street cars should be avoided (*12*).

Station Area Infrastructure

Lighting, cleanliness, and sanitation increase the level of comfort of a transfer station. Generous space on platforms and in aisles not only allows high passenger frequency but also makes passengers feel comfortable (*19*). Platform surfaces, platform heights, and same-level entries have great influence on customer satisfaction (*20*).

Security

Security during “outside of vehicle time” has shown to be one of the leading factors of anxiety (*5*). Criteria for security in public transport ranges from design (crime prevention through environmental design), prevention, and security personnel, through to monitoring, and finally better lighting and colored surfaces. Natural and artificial light as well as cleanliness improves the feeling of safety and comfort, which is especially relevant in underpasses and during nighttime, but also during the day (*7*, *12*, *19*). Finally, organizational measurements help to improve cleanliness and safety feeling (*20*).

Waiting and Sanitary Facilities, Sheltering

As transfer waiting and sanitary conditions rank high in evaluation of passengers, special attention needs to be drawn on waiting areas, sheltering, and sanitary facilities during the design process (*5*, *20*).

Shops

Linked schedules and short waiting times are more important for travelers than generous services and shopping facilities (*19*, *20*). Nevertheless commercial activities inside the interchange can spread out to ignite or regenerate economic progress around the site (*19*).

Parking

Improving the journey to the station, for example, through higher capacity car parks and bicycle parking facilities, is likely to increase rail use by making passengers more satisfied with the service provided for them. Promoting existing car parks as park-and-ride or supplementing unguarded bicycle parking facilities with guarded facilities showed to be less efficient (*7*).

Hub Architecture

There is a strong correlation between the overall optical impression of hub layout and passenger satisfaction (*18*, *20*). The amenities provided in terms of the physical characteristics of the transit station such as visual comfort provided by architectural design, however, are less important than good connections. The station environment should be simple and straightforward (*5*).

DESIGN METHODOLOGY

This paper presents a design methodology that follows directly from analysis of key success factors. The methodology comprises classification, approach, and design all in one highly iterative process and can be used as a practice-ready design stencil.

Three-Stage Design Process

With the integration of classification, an approach stencil, and design into one iterative process researchers guarantee that interdependencies between individual design decisions are taken into account and lead back also to earlier design stages. The classification stage is first used to check which design parameters apply for the individual hub, leading to a set of best and worst practice model hubs. The approach stage ensures that all decisions from the large-scale location decision down to microscopic pedestrian flows are modeled, verified, and reproducible throughout the whole process. Finally, the design stage allows the integration of the two earlier stages into an overall design, yet with feedback loops to all relevant earlier decisions. By this means the overall design of an integrated hub will incorporate all planning stages together and with the effect that no feature from later design stages will contradict decisions from earlier phases.

Hub Location

First and foremost, make use of three major design strategies that exist in any planning area: the urban development plan; the design philosophy for route network design of the public transport network; and the target street, bike, and pedestrian networks.

It is possible to retrieve the existing and planned urban centers from the urban development plan. Researchers obtain the network design philosophy from the public transport route network design, and this yields among other points, those lines that are to be clustered at common stops. Finally, researchers deduct the target street, bike, and pedestrian network from traffic planning.

Station Area Design

While at first sight, it is clear that all types of public transport that occur in the hub need to be taken into account, a more detailed view presents several challenges to meet the hub's design targets. Therefore, the individual station areas within a hub require distinct design approaches. Additionally, the typical travel distance of the lines affected (long distance, regional, or urban) leads back onto (1) the presumable time spent in the hub, (2) the acceptable length and layout of passenger flows, (3) the need for more comfortable waiting spaces and luggage storage, and (4) the type of shops and amenities needed.

From a first network-based public transport demand assignment, researchers obtain the transfer relations and quantities within and between the station areas. This allows for a rough arrangement of the station areas. Despite the fact that travel demand and service frequency may change over the years, hub design depends on the frequency and the service hours of each transport mode, including the expected passenger flows.

It will then be necessary, however, to design a target timetable for all the public transport lines affected, in order to know the individual track, berth, and station occupancies of each line. Only then will the precise dimensions of the infrastructure needed for each station area be known, and only then will researchers also know about the passenger flows. If the infrastructure was designed first and then the timetable, researchers might be confronted with undesirable transfer conditions, infrastructure constraints, or misplaced hub layouts.

Once a detailed timetable and a detailed hub layout on the public transport side have been designed, a timetable-based demand assignment can be carried out. These results are then used for a preliminary fine-tuning of the timetable, the station areas, and the hub layout.

Incorporation of Surroundings

One major fundamental difference yet to be tackled is the previous existence of an urban center at the very location of an intermodal hub. The hub needs to be interwoven into the urban fabric to make use of shared facilities and amenities and to ensure that the hub is perceived as an attractive place to stay. The design process is separated here to allow a design of both newly built hubs and hubs in existing urban centers.

The insertion of a hub into an existing urban center is a process of high sensitivity for existing structures. Since researchers want an intermodal hub to be incorporated in the best manner possible, they first need query all relevant data about the center: the existing sales area, existing parking and bicycle stabling, and existing sanitary facilities. Researchers also derive any planned or desired changes to this structure from the urban development plan. The new hub needs to complement, rather than rival the existing one in order to allow for the best possible integration of the two.

If the hub is to be built from scratch, it might appear easier at first sight to incorporate it into the environment. But the nature of a completely new structure, however, requires extensive market research on the retail side of the hub to ensure the added value of an integrated hub with both transport and amenities for several user groups.

Intermodal Facilities

Although park-and-ride can be successful, even in locations with only minimal infrastructure, it is desirable in a multimodal transport environment to incorporate the design of parking lots and bike stabling facilities into the design process rather than simply building a parking garage next to a station building.

The space per person needed for stationary traffic increases walking distances within a hub drastically. The more decentralized a public transport network, the closer the hubs are to the origin of multimodal trips, the more walking that is needed between parked automobiles and public transport contributes to the overall trip duration and therefore mode choice. Furthermore, parking garages tend to be filled from the closest to the farthest lots, the average trip length increases with the occupancy of the garage.

Again, the pedestrian flows within the station form a crucial part of the traffic model and are coupled to the infrastructure design via feedback loops.

Amenities

The demand for the type and quantity of waiting areas, retail areas, kiosks, information/ticketing counters, and sanitary facilities can be derived in dependence on the duration of stay in the hub, as evaluated above. Amenities should to be allocated directly along the main transfer passenger flows as those off-stream tend to fail.

Information Design

As remarked above, the quantity and quality of the information design depends upon (1) the type of traffic affected (long distance, regional, or urban), (2) the projected stay within the hub, and (3) the share of unaccustomed passengers transferring. The quality of information given largely depends on the integration of planning and operation within the multimodal environment, which again leads back to the importance of public transport alliances. The quality of information gains even more importance in case of service disruptions, so that passengers can be seamlessly informed about detours, replacement services, and travel alternatives. The desired quantity and quality of this information needs to be fixed from the start in order to be able to reserve prominent spaces, which are clearly set off from advertisements and all other optical distractions.

Architecture and Insertion

This clear form-follows-function approach leads to an infrastructure designed to optimally meet the needs of an intermodal urban hub, without being restricted by budget or existing conditions that cannot or will not be changed. Since this paper presents a modular approach, in principle these modules can then be molded into an architectural and urbanist overall design. However, as most decisions have been based on walking distances and transfer attractiveness, the architectural design process needs to work together closely with the earlier design steps, meaning later design decisions need to invoke feedback loops to earlier design stages.

There will always be restrictions to be faced of course, either stringent or less so concerning available space, funding, or urbanism issues. These issues, however, can be best tackled if the target is clear from the beginning and the arrangement of interdisciplinary feedback loops has been decided upon and maintained from the start.

Three-Stage Framework

The 3-stage framework in Figure 1 helps to compare and evaluate existing transit hubs as well as to point out shortcomings of future designs, including quantitative and qualitative indicators. The classification of hubs is done by means of both qualitative and quantitative indicators. While this paper uses the former mainly for clustering purposes, the latter, highlighted in Figure 1, are used for comparison within the clusters and subsequent design.

Transit key performance indicators (T-KPI) define the overall performance of a hub. These indicators form the first stage of hub type clustering and initiate the timetable coordination process. Operational design parameters (ODP) form the key design element for the transit side infrastructure of the hub. They include all information about vehicles and their interaction with the infrastructure. Since this information is directly derived from the timetable coordination, this is where the form-follows-function approach mainly happens. Finally, hub infrastructure ondicators (HII) cover all parameters connected to the hub infrastructure. These are split into (1) individual traffic parameters, (2) amenities parameters, and (3) infrastructure design parameters.

EVALUATION OF SELECTED HUBS

Methodology

As noted beforehand, the analysis of success factors was based on both literature review and empirical evaluation. From a set of various hubs across central Europe, a set of 14 hubs (in central Europe) was selected for an in-depth analysis. For a better analysis of intermodality, five hubs without LRT connections were added to the analysis. Geographic information systems, official facts and figures, and personal interviews were combined.

The hubs were analyzed along the criteria from Figure 1 and best and worst practice examples were derived. Furthermore, researchers extracted design modules to be used in the design methodology. Finally, they aligned the extracted key factors with the literature research. Table 1 lists transit hubs in medium-size cities as well as in major cities.

Integration into the road network was evaluated as (1) connected to roads of low importance, (2) located to a through road, and (3) located at a highway. Integration into the bike network was evaluated as (1) no connection to a bike network, (2) connected to bike network by appendix, and (3) located at a route of the bike network.

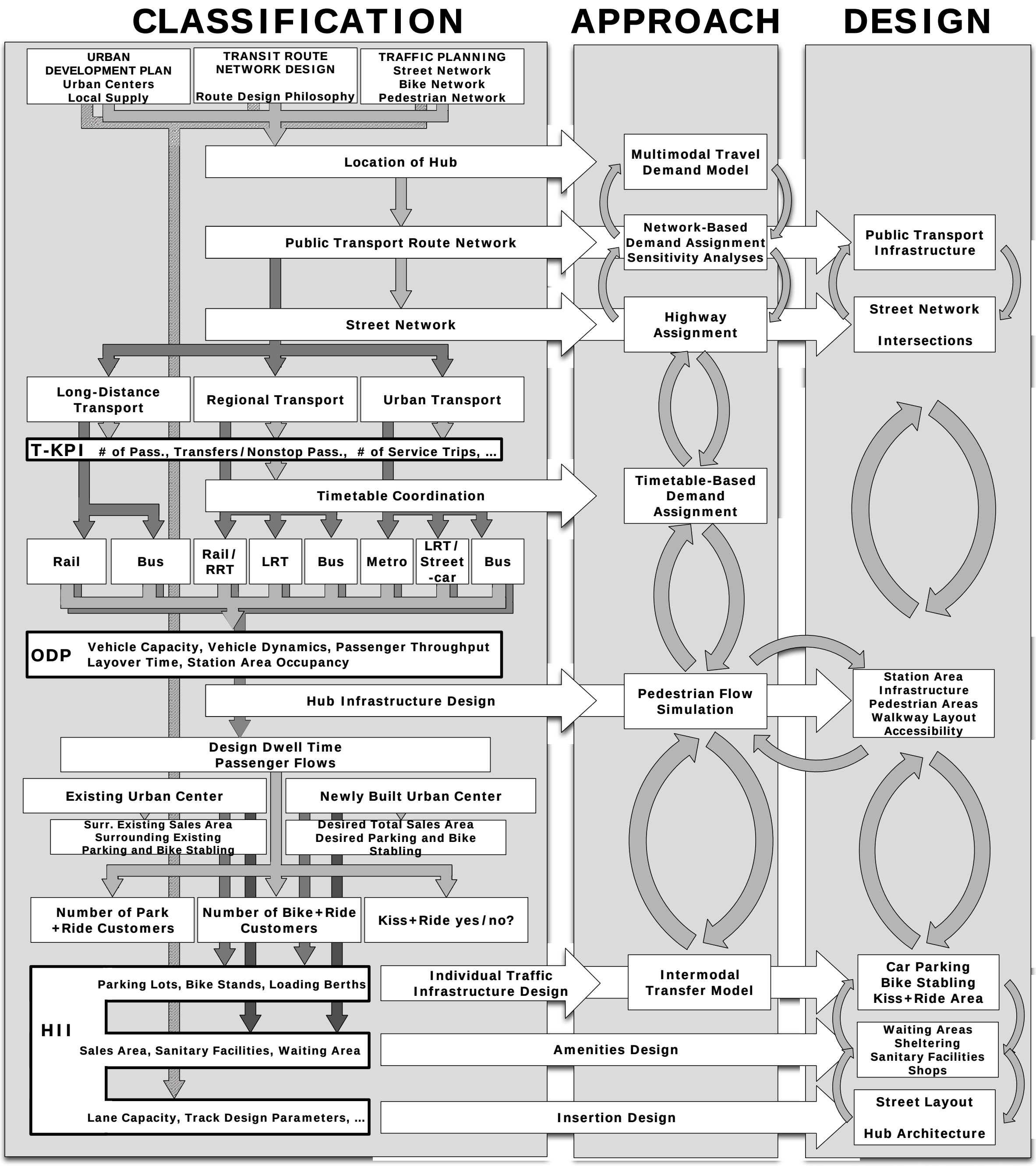

FIGURE 1 Three-stage framework to analyze transit hubs (grey shading of arrows only for readability).

TABLE 1 Data and Key Factors of Analyzed Hubs

Hubs Features		Medium-Size Cities							Major Cities						
		Graz–Andritz	Graz–Don Bosco	Graz–Murpark	Graz–Puntigam	Karlsruhe–Zündhütle	Salzburg–Main Station	Salzburg–Gnigl	Vienna–Aspern	Vienna–Ottakring	Munich–Fröttmanning	Munich–Pasing	Munich–Arabellapark	Prague–Černý Most	Prague–Hradčanská
T-KPI															
Total area hub (km²)		4	8	4	5	3	32	2	11	12	1	25	13	15	15
No. of pass./day	Long distance	—	—	—	—	—	—	—				9k		—	—
	Regional	—	2k	1	—	1k	14k	5k	NA	NA	NA	11k	NA	5k	2k
	Urban	14k	17k	8k	9k	10k	11k	5k				21k		55k	70k
No. of trips/day		580	978	618	731	566	2,370	394	1,220	2,400	432	2,487	886	2,104	2,514
Pass. capacity/day		59k	95k	60k	73k	64k	336k	63k	188k	383k	111k	307k	150k	278k	411k
Pass. capacity:ratio longdist:regional:urban		0:0:1	0:1:2	1:9:19	0:1:2	0:1:31	0:4:3	0:1.1	1:11:20	0:0:1	0:0:1	1:3:6	0:0:1	0:1:12	0:1:29
Ratio of transfers/nonstop pass.		7.4:1	1:4.3	8.3:1	10.1:1	1:2	3:1	1:1.3	1:0	3:1	0:1	1:1	2:1	1:2	1:2
HII															
Walkway layout	Max. distance between different modes (m)	100	250	500	250	200	400	150	200	250	550	400	250	650	550
	Max. no. of location of service facilities (m)	150	—	350	350	200	200	—	100	350	—	200	350	550	200
Percentage of handicapped-accessible berths (%)		100	100	100	100	100	100	100	100	100	100	100	100	100	100
Stopover function (Y/N)		Y	N	N	N	N	Y	N	N	Y	N	Y	N	Y	Y
Sales area	No. of stores	<10	—	>10	—	—	<10	—	—	—	<5	>10	<5	<5	<5
	Area (m²)	<500	—	>1,000	—	—	<500	—	—	—	<100	>1,000	<100	+1,000	<500
Sanitary facilities (Y/N)		Y	N	Y	Y	N	Y	N	Y	Y	N	Y	Y	Y	Y
Waiting areas	No. of seats	<25	<50	<25	<50	<25	>100	<25	<50	<50	<25	<100	<100	+100	<100
	% indoor seating	0%	0%	0%	20%	0%	60%	50%	70%	0%	0%	30%	30%	50%	70%
No. of parking lots		<100	<100	<500	<100	<100	<500	<100	<100	<500	>1,000	<100	<100	<1,000	<100
Integration into superior road network (quality 1–3)		1	2	3	2	2	1	2	2	2	3	2	2	3	3
No. of bike stands		<100	<100	<500	<100	<100	<1,000	<100	<500	< 100	<100	>1,000	<100	<100	<100
Integration into bike network (quality 1–3)		3	2	2	3	3	2	2	2	3	1	3	3	1	1
Kiss-and-ride berths (Y/N)		N	N	N	N	Y	Y	N	Y	Y	Y	Y	N	N	N
Taxi stand (Y/N)		Y	N	N	Y	N	Y	N	N	Y	N	Y	Y	N	N

Note: NA = not available; Pass. = passenger; k = thousands.

Best and Worst Practice Examples

The full range overview of 50 hubs and in-depth study of 14 hubs is available in the complete study. The most prominent examples that best underline the findings are presented here.

Murpark, Graz, Austria

Murpark Station was built from scratch in 2007 between the A2Z motorway and the Ostbahn Railway. It features a streetcar extension to reach the hub as well as the rerouting of all urban, regional, and long-distance bus lines to serve the hub. A motorway exit, a park-and-ride center, and a new S-Bahn railway stop have been built and together enclose a shopping center. The whole project has been embedded into a major road reorganization program: the area south of the hub is currently seeing the construction of a major ring road, pulling individual traffic off the current radial roads toward the aforementioned radial motorway. The motorway can thus be used for influx metering and a diversion of traffic to the parking area. The station area for bus, streetcar, and railway; the parking; and the shopping area as well as all road and bicycle network attachments have been designed jointly. At 8,000 passengers a day (with figures sharply rising), of which 89% use the station for transfers, the hub has become a major transfer hub straightaway.

Puntigam, Graz, Austria

The original train station of Puntigam has been moved to the north to align with the outer ring road and a major arterial road. Streetcar line 5 has been extended one station southward to directly underpass this new train station and serve a completely new hub directly adjacent.

The surrounding area, currently undeveloped, is to see major urbanization in the coming years, with the hub serving as an urban center. With 9,000 passengers a day, almost exclusively transfer passengers, this station has become a major transit hub within Graz. The hub is served by three major and two local bus lines and features park-and-ride and kiss-and-ride facilities, a taxi stand, a kiosk, and a toilet. Furthermore, the hub is located directly at two main bike routes and features a bike shed.

Andritz, Graz, Austria

Andritz has always been the district's center, with high-density retail and service facilities. The streetcar terminus, formerly located offside, has been reconstructed to be included in the urban fabric, so the former street intersection has turned into an open square. The hub is served by two streetcar lines and three major and several minor local bus lines (Figure 2). Several amenities are located within the turning loop, and part of the square is now used as a market place. The hub is located on two main bike routes and features several bike sheds. The hub features kiss-and-ride but no parking facilities. Out of 14,000 passengers a day, 20% have the hub itself as their origin or destination, and another 60% are transfer passengers.

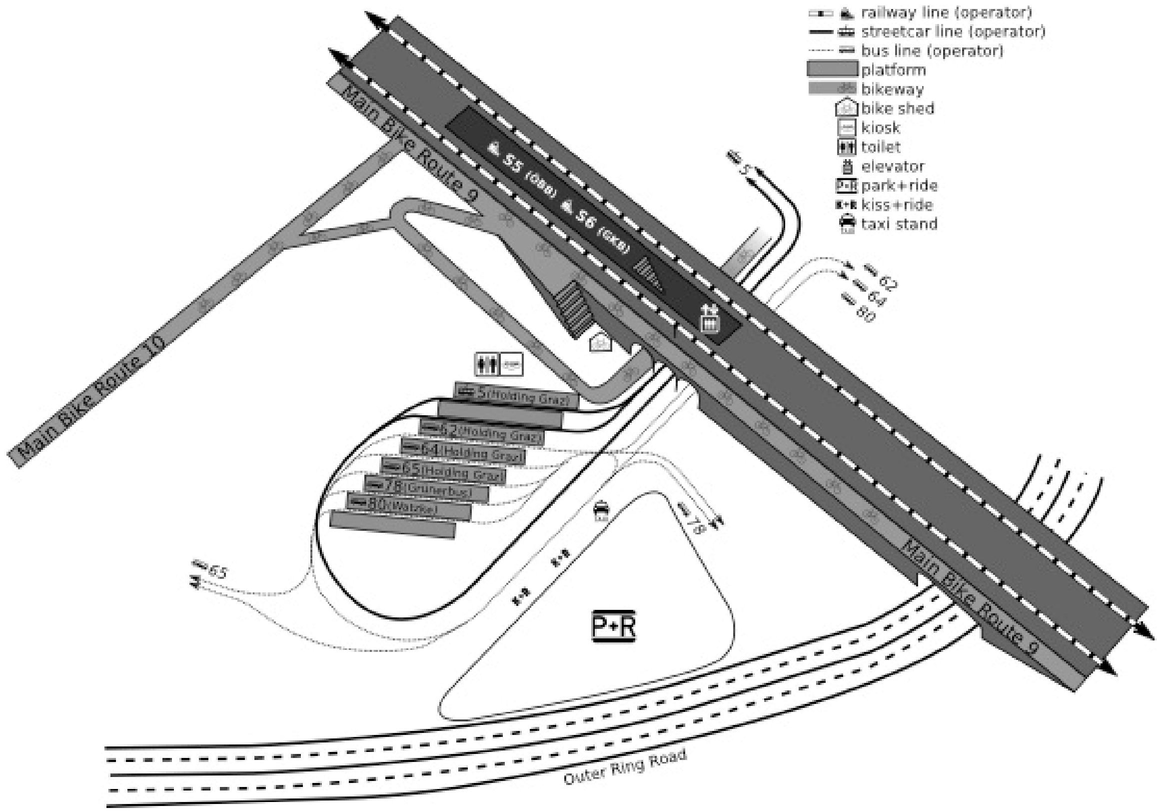

FIGURE 2 Multimodal hub Puntigam in Graz, Austria.

Don Bosco, Graz, Austria

The Don Bosco train station, located 3 km north of Puntigam, has been inserted on the existing railway to allow for an improved transfer of S-Bahn passengers to the city center. The station is linked to the city by a high-quality bus service (peak headway 2 min) and is served by three out of six S-Bahn lines in Graz. Even of similar appearance as Puntigam, however, out of 19,000 passengers a day, only one in five passengers do actually transfer there, the rest being nonstop passengers. The surrounding areas are mostly industrial real estate without current development perspective. The hub itself features no amenities apart from seating. The hub is linked to the bike network only by a stub off the main bike routes. Currently, the bike shed is mainly unused, and two of five bus platforms are used for bus parking.

Discussion of Results

The evaluation of Table 1 along with quantitative data can be split into two parts: correlations between quantitative aspects and key factors of success and failure. The former is straightforward and little surprising and aligns perfectly with literature. It can be summarized as

- The greater the number of nonstop passengers, the less successful the facilities at a hub.

- The greater the transfer distances, then exponentially fewer people will choose and use it from among all the possibilities.
- The more dominant changing transit becomes, the more focus needs to be put on not only on amenities, but even more on urban integration.
- The more integrated the timetables, the more passengers use transfers.

Key factors of success or failure, on the other hand, feature some less obvious results:

- The existence of public transport alliances not only fosters but dramatically pushes transfers between different modes of public transport.
- Only a combination of push factors in individual transport (overcrowding, parking management, traffic calming, etc.) and pull factors in transit will lead to an increased ridership and therefore lead to successful intermodal hubs.
- Only an integrated design of urban development, road network, and transit can yield a successful role of a hub as both a transfer hub and an urban center.
- Public transport alliances push transfers not only through ticketing via different bus, tram, and light rail operators but moreover provide a common interface to the user including passenger information at each hub.

Finally, T-KPI and HII provide a guideline of factors to be considered during the assessment and design stage of hubs.

CONCLUSION

This paper identifies the most important success factors by evaluating both classical planning strategies found in the literature and actual projects of multimodal integration. This approach shows that there are several very basic yet crucial success factors. An integrated management and planning framework is essential for achieving an integrated multimodal transportation network. Public transport alliances, usually considered to mainly improve the accessibility of a transit system, offer a framework for an integrated multimodal planning approach that pushes the willingness to a holistic multimodal hub design. Timetable-oriented network design together with attractive transfer conditions for passengers also proved to be important. One important factor is quite simply the location of a hub. This needs to align with urban subcenters in order for local demand attractors to form synergies with passengers transferring at the hub. Hubs strengthen subcenters by bundling service institutions. Also, the location needs to reflect the total multimodal transport network layout to allow for a maximum bundling of transit lines and auto/bike routes and thus achieve a network effect by its mere position.

This integrated approach allows for an adequate hub design and a long-term alignment of spatial planning and transport engineering. Several fields of engineering are involved since there is a need for travel demand modeling, cooperation with urban planning, design of public transport, and also road infrastructure planning.

Future developments in Graz and other European cities include further modes such as e-bike sharing and e-car charges. Additionally locations for district parcel service and regional logistic centers will be embedded within transit hubs.

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Streetcar Institutional Models
Comparison of Experience with Transit Coordination

CHRIS KOPP
TERRY NASH
ASHLEY BOOTH
MATT WEBB
HNTB Corporation

SUE COMIS
Sound Transit

SHELLIE GINN
City of Tucson

BENJAMIN LIMMER
Atlanta BeltLine, Inc.

JEFF POLENSKE
City of Milwaukee

Four institutional models have emerged for the introduction of modern streetcars in North American urban environments in recent years: city-led, transit agency–led, privately led, and hybrid. In each case, the institutional relationship with other transit operators in the streetcar service area differs. This paper explores the different approaches, requirements, challenges, and outcomes as they relate to coordination of modern streetcar services with existing and planned transit services. A particular focus is on the customer experience aspects of the streetcar's design, construction, and operation in the context of the urban transit system. Five dimensions of coordination are compared and contrasted using case studies from Atlanta, Detroit, Milwaukee, Tacoma, and Tucson. Dimensions include physical, service, fare, information, and construction coordination. Using case study narratives and comparison tables, the challenges faced under the various institutional arrangements to introduce modern streetcar as an integrated component of a regional transit system are compared. The relative strengths and weaknesses of the different institutional models are discussed based on North American implementation experience.

INTRODUCTION

Modern streetcar systems are gaining popularity as a high capacity mode of transit in dense, urban environments where the benefit of rail is desired but preclude separated guideways. Around the United States, these systems generally share common goals of increasing nonautomobile mobility and guiding and promoting economic development. Streetcar systems enjoy a higher freedom of flexibility by being able to run in mixed traffic, negotiate tight radius turns, and feature low-floor vehicles capable of level boarding.

In the past 15 years, four institutional models have emerged for their funding, construction, and operation:

1. City-led. Municipal governments identify a preferred corridor for streetcar investment as part of an economic development strategy, assemble funding, manage project development, and subsidize operations and maintenance. Examples include early installations in Portland and Seattle, the recently opened system in Tucson, as well as the ongoing projects in Cincinnati, Kansas City, Milwaukee, and Washington, D.C.
2. Agency-led. Transit operators introduce modern streetcar as part of their portfolio of services. Examples of this structure operate in Tacoma, Dallas, and Salt Lake City and are planned for Santa Ana and Tempe.
3. Privately-led. Corporate sponsors and philanthropic foundations form a not-for-profit corporation to build and operate a modern streetcar using largely private funds. Examples include the M-1 RAIL project currently under construction in Detroit.
4. Hybrid. Different agencies are responsible for the development and operation of the streetcar system. Examples include the recently opened system in Atlanta as well as projects planned in Fort Lauderdale and Los Angeles.

In each case, the institutional relationship with other transit operators in the streetcar service area differs. Senior implementation team members from five streetcar systems were surveyed to explore the different approaches, requirements, challenges, and outcomes as they relate to coordination of modern streetcar services with existing and planned transit services. The streetcar systems are summarized in Table 1.

Five dimensions of coordination were explored with streetcar system representatives:

1. Physical coordination. How does the streetcar connect with other transit systems at transfer points?
2. Service coordination. How are schedules aligned with connecting transit services?
3. Fare coordination. What policies are in place to facilitate seamless travel on the streetcar and other transit services?
4. Information coordination. How is the streetcar positioned in traveler information materials and systems as part of the larger transit system?
5. Construction coordination. How is the project delivered and how are construction challenges coordinated with existing road and transit agencies?

The following sections summarize the findings from each system along each dimension of coordination.

TABLE 1 Streetcar Systems Surveyed

	Atlanta Streetcar	Detroit	Milwaukee Streetcar	Tacoma Link	Tucson SunLink
Institutional model	Hybrid	Privately led	City-led	Agency-led	City-led
Implementation status	Operating	Construction	Final Design	Operating	Operating
Streetcar owner	City of Atlanta	M-1 RAIL	City of Milwaukee	Sound Transit	City of Tucson
Line Length (route miles)	1.4	3.1	2.1	1.6	3.9
Boarding platforms	12	20	23	8	23
Boarding platforms with nearby connecting services	7	8	11	6	8
Major connecting services	MARTA heavy rail and bus at Peachtree Center; MARTA bus at Woodruff Park	People Mover and bus at Congress; People Mover and bus at Grand Circus; Detroit DOT and SMART bus at MLK; Detroit DOT and SMART bus at Warren; Amtrak at Baltimore; Bus at Grand	Amtrak, intercity, and MCTS bus at intermodal station; MCTS bus at Wisconsin Avenue	Sounder Commuter rail; Sound Transit Express; Pierce Transit, Intercity Transit, and Greyhound bus (and in 2017 Amtrak) at Tacoma Dome; Pierce Transit bus at all stations	SunTran bus at Congress and Granada; SunTran bus at Congress–Broadway and Church; SunTran bus at Ronstadt Transit Center; SunTran bus at Boardway and 6th; SunTran bus at Helen and Warren

PHYSICAL COORDINATION

This criterion focuses on the physical coordination, or actual connection, between streetcar lines and existing rail and bus transit. An ideal outcome from a customer perspective would be the ability to board a connecting transit service at the same station, plaza, and/or platform where one alighted the streetcar, or vice versa.

Among the streetcar systems reviewed, connecting transit services were generally located within one block of streetcar stops, typically involving fewer than two street crossings to reach the boarding area of the connecting transit service. Streetcar systems frequently had nearby bus stops in the same block or an adjacent block but did not share platforms. Reasons included

- Concerns about wheelchair ramp or lift compatibility on buses and the raised platforms used at streetcar stops for level boarding.
- Concerns about buses blocking streetcars during the extra dwell time at stops required to secure wheelchairs on buses.
- A desire to maintain a separate identity for the streetcar service, particularly in contrast to existing local bus services.

SERVICE COORDINATION

An ideal service coordination outcome from a customer perspective would be the ability to have a connecting transit vehicle waiting when the streetcar arrives to facilitate a timed transfer from streetcar to the connecting transit service, or vice versa.

Among the streetcar systems reviewed, streetcars were considered to operate at sufficiently frequent service throughout enough of the day to facilitate convenient transfers with other services (Figures 1 and 2). No instances of changes to streetcar schedules or the schedules of connecting transit services to reduce the wait time for transferring passengers were identified.

Two examples have streetcar lines that connect with commuter and intercity rail services. Sound Transit's Tacoma Link system connects with its Sounder commuter rail service and Sound Transit express buses at the streetcar end-of-line terminal at Tacoma Dome Station (Figure 3). Tacoma Link's service hours coincide with Sounder's peak-hour directional commuter rail service to and from Seattle, as well as the Express buses using the Tacoma Dome Station. Many riders use Tacoma Link as a "last mile" connection to and from these long-distance transit services.

Tucson's SunLink has a station within three blocks of the Amtrak station, which is on the Sunset Limited route connecting New Orleans with Los Angeles with one train daily in each direction. Both the eastbound and westbound trains stop in Tucson within the streetcar service hours.

M-1 RAIL is constructing a station adjacent to the existing Amtrak station in the New Center area of Detroit. This station will connect M-1 RAIL passengers with Amtrak's three round trips between Detroit and Chicago on the federally designated High Speed Wolverine line.

FIGURE 1 The Atlanta Streetcar stop is immediately outside the portal to the MARTA Peachtree Center Station.

FIGURE 2 MARTA has placed directional signage on their heavy rail platform at Peachtree Center Station guiding patrons to the Atlanta Streetcar stop.

FIGURE 3 Tacoma Link was designed with a stop across a pedestrian-enhanced street from the Sounder commuter rail station. The Tacoma Dome Station park-and-ride garage is also adjacent. The Pierce Transit and Sound Transit bus platform as well as the Greyhound station are directly behind the garage.

FARE COORDINATION

An ideal fare coordination outcome from a customer perspective would provide reciprocal transfers with full credit for previous fares paid between the streetcar and all connecting transfers using all valid fare media.

Among the streetcar systems reviewed, there was a range of levels of fare integration. Connections for which the streetcar implementing agency is the same institution as the operating agency of the connecting transit service demonstrated the greatest fare coordination.

Among the streetcar systems reviewed that are currently in operation only Tucson offers full integration of fare media across streetcar and connecting transit services. All Sun Go fare media are accepted on the Sun Link streetcar as well as Sun Tran bus services. Coordination was simplified in Tucson by an institutional arrangement in which the City of Tucson, which managed the design and construction of the Sun Link streetcar, also controls Sun Tran, the regional transit agency.

In Atlanta and Tacoma, the streetcar services were introduced with free fares, eliminating the need for coordinated fare systems. Both systems are transitioning to fare payment systems that will accept regional electronic fare media as valid forms of payment on streetcar services. In Atlanta, the Breeze contactless farecard is valid on MARTA heavy rail and bus services (Figure 4). In Tacoma, the ORCA contactless farecard is valid on Sound Transit and six other transit agencies in the Puget Sound region. Both systems will facilitate free transfers between the streetcars and connecting transit services or credit for streetcar fares paid when boarding services with higher fares.

FIGURE 4 Four *Breeze* ticket vending machines in MARTA Midtown Station. The same equipment is used for heavy rail and streetcar tickets.

In Detroit and Milwaukee, implementing organizations are currently developing policies that will facilitate transfer discounts between streetcar and connecting local transit services operated by others. In Detroit, the introduction of proof of payment to the region on the streetcar system is taking place as other agencies, including a new regional transit authority, are in the early stages of developing a regional farecard and bus rapid transit services that will also use proof of payment.

INFORMATION COORDINATION

An ideal information coordination outcome from a customer perspective would be the clear presentation of streetcar services and all connecting transit services on all maps, schedules, mobile apps, and other transit service information materials, as well as wayfinding signage showing the way from streetcar stops to boarding platforms of nearby transit services, and vice versa (Figures 5 through 8).

Among the streetcar systems reviewed, Tucson has achieved the greatest level of coordination between streetcar and bus service information. Sun Link streetcar and Sun Tran bus information is available on streetcar stops, on both websites, and in social media. Sun Tran rider guides include information for both the streetcar and bus systems. The maps located at the streetcar stops show the location of connecting bus routes. The bus stops do not include the streetcar information except on system maps that are posted at transit centers. Sun Tran's mobile app display integrated service information for streetcar and bus services.

In Tacoma the Sound Transit system map shows Tacoma Link streetcar, Sound Transit-operated Express Bus, and Sound Transit-operated Sounder Commuter Rail service. A policy to show connecting transit services, such as local bus services operated by Pierce Transit, on system maps, at streetcar stations, via wayfinding signage, is under development. Pierce Transit system maps show Tacoma Link's route and station locations. Pierce Transit's online trip planner provides results using Tacoma Link, although the origin and destination information must match the Tacoma Link station names. Nearby addresses default to Pierce Transit bus routes.

CONSTRUCTION COORDINATION

An ideal construction coordination outcome from an implementation agency perspective would be to have a coordinated project with the advancement of required utility relocations occurring prior to active construction of rail and system elements regardless of the order of magnitude of construction scope of work.

Among the streetcar systems reviewed, a wide variety of construction scopes of work were implemented in conjunction with the construction of the streetcar system. For example, in Detroit, the majority of the Woodward Avenue corridor which M-1 RAIL will operate is being completely reconstructed in close coordination with the Michigan DOT. In comparison in Atlanta, the track slabs were placed within existing streets with minimal reconstruction.

FIGURE 5 Tucson's Sun Link system was designed with a stop across the street from the downtown bus transit center. This, along with other bus connection points, is illustrated on the Sun Link system map.

FIGURE 6 Atlanta Streetcar A-Line service map depicts MARTA stations in the vicinity.

FIGURE 7 MARTA rail map lists all regional transit providers, including Atlanta Streetcar.

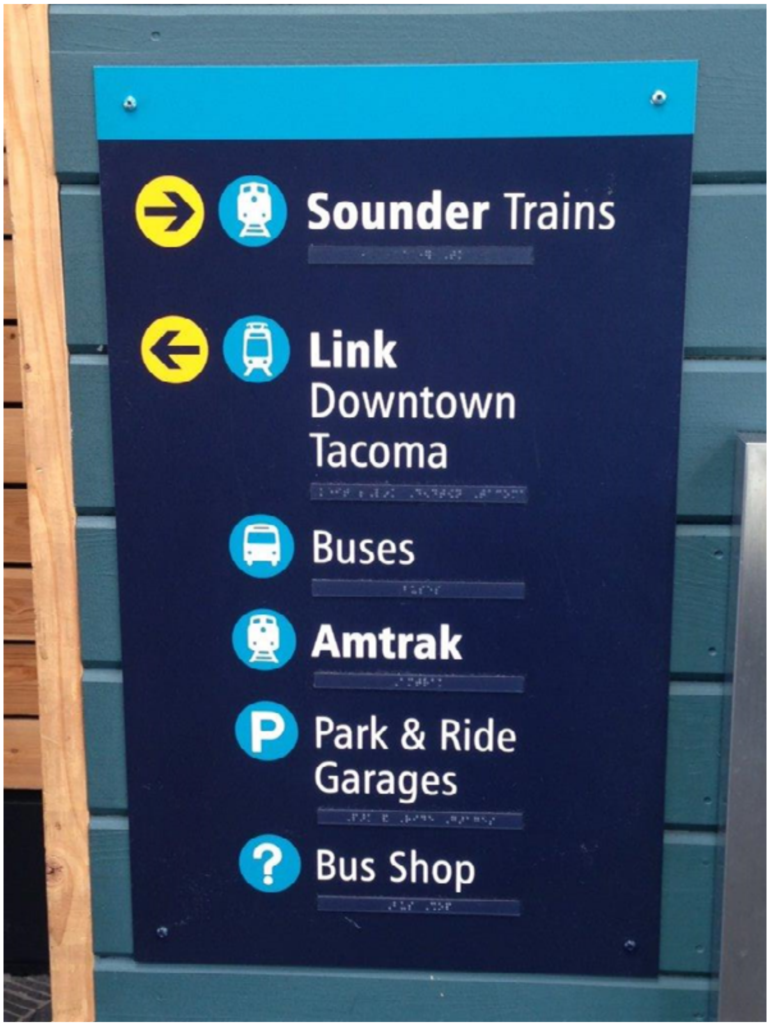

FIGURE 8 Sound Transit provides directional signage throughout the Tacoma Dome Station regional transit hub guiding patrons to the interconnecting services.

The limits of construction primarily stopped at the edge of the streetcar track envelope or the station platform. Regardless of the intensity of the construction scope of work, a key lesson learned with all streetcar systems is the need to coordinate early and often with impacted utilities (Figures 9 through 11). In Detroit, this meant reaching out to impacted utilities three years in advance during the planning and environmental phases. This outreach led to the development of an corridorwide integrated 3D model of existing utilities and planned M-1 RAIL streetcar infrastructure. This 3D model was used by the contractor and local public and private utility companies to assist in finalizing the relocation scope of work for utilities. This 3D model was also used in the field to help field locate necessary design modifications during construction due to unforeseen discoveries during construction.

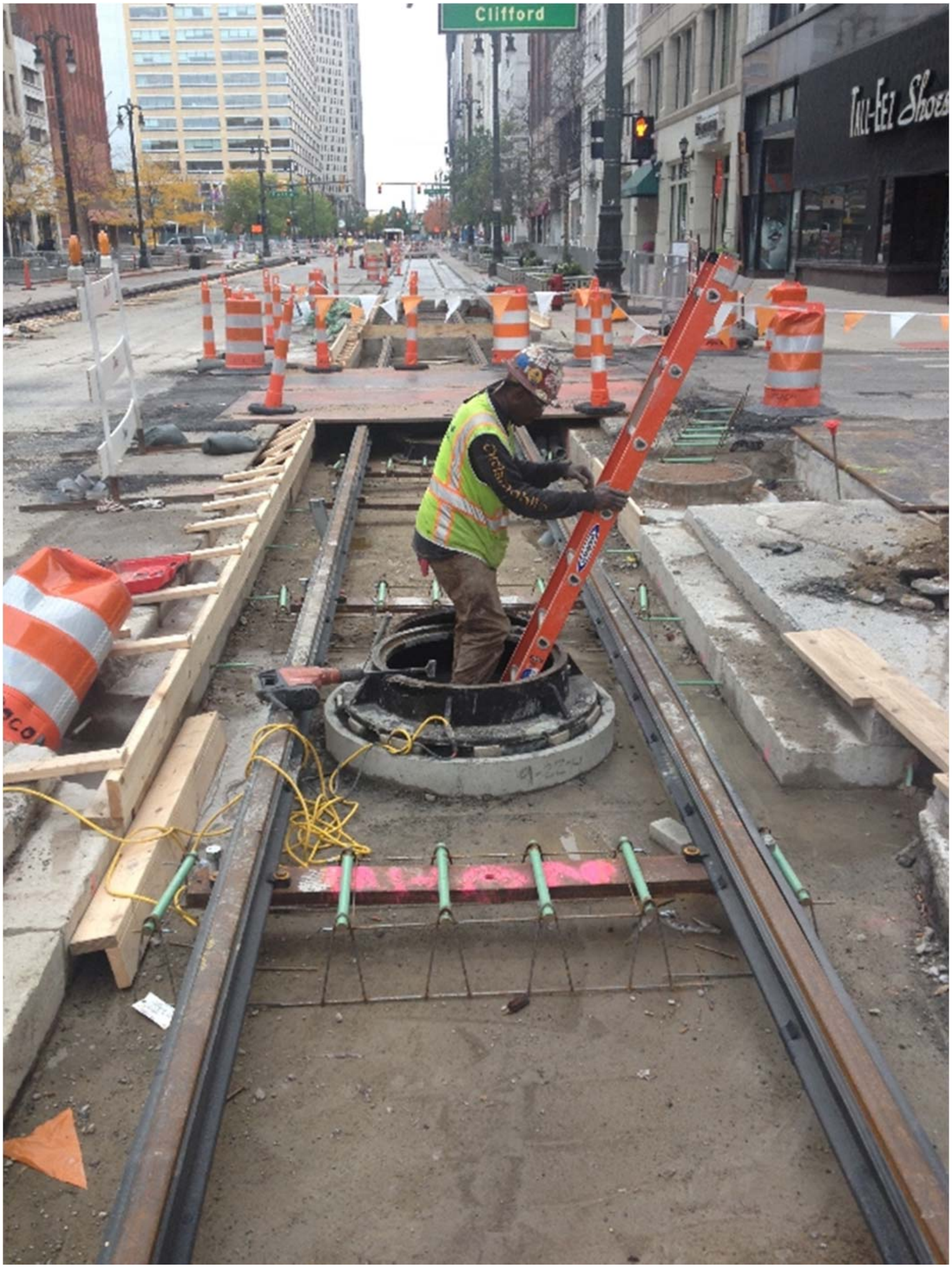

FIGURE 9 Construction of the M-1 RAIL streetcar required reconstruction of streets that had 300 years of utilities and other infrastructure beneath them.

FIGURE 10 In Atlanta construction limits involved substantially less street reconstruction.

FIGURE 11 The City of Tucson was able to use its franchise agreements with utilities to minimize the costs of the utility relocations for the streetcar project.

Construction progress in Detroit was challenging given the complex three-party contract that was executed between M-1 RAIL, Michigan DOT, and the CM/GC contractor, Stacy and Witbeck, Inc. This delivery model was implemented due to the desire of M-1 RAIL to have a fixed guarantee maximum price, while Michigan DOT was willing to accept additional risk and chose to implement a low-bid type contract to implement the Michigan DOT scope of work.

In Tucson, the city utilized the design-bid-build method of construction. The benefit to the city in constructing the streetcar was the ability to take advantage of its franchise agreements with utilities. This resulted in minimal cost to the project for utility relocations. Another benefit was the city's ability to control permitting and coordination with other city departments.

CONCLUSIONS

Achieving the goal of ideal transit coordination faces many technical and logistical challenges, as described above. But each of these success stories demonstrates that a common goal of integrating a streetcar into the regional transit network overcomes institutional challenges. These examples illustrate how streetcar systems can be integrated into legacy bus and rail networks, and considered part of the total transportation network with coordinated branding, customer information, and fare structures.

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Achieving Optimal Results from New Light Rail Lines
Lessons from Three Decades of Experience

KEN ZATARAIN
TriMet

MAVRICK FITZGERALD
Florida State University

Portland's TriMet is one of the most successful transit agencies in the United States in terms of ridership and public support. Five light rail projects provide the framework of the transit system, supported by a high-frequency bus grid route structure. The premise of this paper is that a holistic approach to transit development helps ensure success. Integrating bus and rail for seamless passenger trips is essential and is supported by solid land use planning in the transit corridor, smart station design, and effective public marketing and outreach. These principles are synthesized into a philosophy of the "Complete Trip," which places a premium on the entirety of the rider's trip, from doorstep to doorstep. Examples from TriMet's experience illustrate how these concepts are realized and highlight how each new rail line facilitates innovation by the transit agency and its public and private sector partners.

PURPOSE

This paper presents an overview of the approaches TriMet has successfully used to integrate light rail into the Portland region's transit system. It is based on perspectives gained from 30 years of incremental experience with five new rail lines in a variety of operating environments and a range of economic conditions. Light rail has been a central component of Portland's transit development strategy and has fostered other jurisdictions' increasingly effective transit-supportive policies and plans. Over the decades, with each new rail line TriMet has enhanced the scope of its jurisdictional partnerships to include land use plans for station areas, streetscapes, intermodal access, and marketing. These partnerships, in combination with restructuring bus routes in the light rail corridor, have yielded respectable ridership benefits.

Transit is embraced as a means to achieving broader social, economic, and environmental goals in local, regional, and state policies and plans. Light rail in particular is popular with both the public and policy makers. This status provides the opportunity to innovate: to do things in the context of network design that otherwise could not be achieved without the presence of light rail.

Like many transit agencies, TriMet regards ridership on light rail and the larger transit system as its overriding measure of success, fundamental to TriMet's goals around public service. High ridership results from the building blocks of robust network design (multiple destinations, direct and comprehensible routes, easy connections) and a good level of service (frequency, span, coverage, and reliability). The region's riding habit is one of the highest in the country, with over 65 boarding rides per capita.

Public approval of light rail is another key measure. TriMet has found that public support for transit rests on three pillars. First, spend taxpayer money wisely, both in terms of operational productivity (high ridership and low cost per ride) and project construction (build on time and within budget). Second, project an image of the system that is attractive, dependable, and integrated into the fabric of city. Finally, build partnerships with stakeholders and raise awareness with the public about the benefits of high-capacity transit, particularly as a way to shape growth, which can lead to increased funding for operations and construction. Before the first line opened in 1986, just 49 percent of residents approved of light rail. That approval level jumped to 85% on the opening of the first line and has generally held above 80% since then.

This paper reviews holistically four ingredients for ridership development:

- Network integration,
- Land use partnerships,
- Station access and design, and
- Marketing.

It builds on Thompson and Brown's study of planning factors, which found that the Portland network's success is due to its dispersed nature, a higher-speed, high-frequency light rail network overlaying the local bus system, and use of connections to provide passengers easy access to an array of destinations (*1*). Subsequent research added socioeconomic factors, such as density and income, to the planning factors discussed by Thompson and Brown. It concluded that, "while they have important influences on performance, they are not determinative. Planning and operational decisions about service coverage, access, and multimodal coordination and integration are also important influences on LRT and metropolitan transit performance"(*2*).

OVERVIEW OF TRIMET SERVICE

TriMet serves a 533-mi^2 area with 1.5 million residents. Annual fixed route boarding rides are just over 100 million, about 40% of which are on light rail. Five rail projects were built over three decades, and four lines now operate their routes over parts of those projects' alignments. The eastside line opened in 1986 between downtown Portland and Gresham, Oregon's fourth largest city. Twelve years later a westside project extended tracks from downtown to Hillsboro. The airport extension is a branch of the eastside line between Gateway Transit Center and Portland International Airport. Interstate Avenue is a branch on the east side from Rose Quarter Transit Center to the Expo Center. Finally, added in 2009, the I-205 line is a branch south from Gateway Transit Center to Clackamas Regional Center, while a second light rail alignment on the downtown Portland Transit Mall runs perpendicular to the first (Figure 1). Table 1 presents details on each project.

TriMet's multimodal service development concept seeks to make transit not just a commuter choice for rush hour trips to and from downtown, but also a welcoming and relevant option for a lifestyle choice aligned with the contemporary travel market, serving a variety of trip purposes, times, and locations every day of the week. As such, TriMet pays attention to the various aspects of a customer's journey and how those parts work together to form a complete trip from doorstep to doorstep: customer information, access, land use, street design, and transit service.

FIGURE 1 TriMet light rail network (1986–2009).

TABLE 1 TriMet Light Rail Network (1986–2009)

Project	Lines	Year	Length (miles)	Cost (millions, YOE)	Stations	Ridership (millions, Fiscal Year 2015)	Transit Network	Operating Environment
Eastside	All	1986	15.1	$214	31	18.7 (Blue Line)	Grid and timed transfer	City streets, freeway, rail ROW
Westside	Blue, Red	1998	17.6	$963	20		Timed Transfer	City streets, freeway, rail ROW
Airport	Red	2001	5.6	$125	4	7.4 (Red Line)	Grid	Rail ROW
Interstate Avenue	Yellow	2004	5.8	$350	10	4.7	Grid	City streets
Portland Mall	Yellow, Green	2009	1.8	$576	14	6.5 (Green Line)	Micro grid	City streets
I-205	Green		6.5		8		Grid	Rail ROW

NOTE: YOE = year of expenditure; ROW = right-of-way.

NETWORK INTEGRATION

The success of a rail line depends partially on factors outside a transit agency's control, such as city form and travel costs for automobile drivers. Nevertheless, transit agencies should take decisive steps to ensure the success of rail projects years before they open. TriMet's first light rail line opened in 1986, but the groundwork for Portland's present transit system was laid in 1982 when construction of the line began. This was a heroic undertaking that completely revamped the majority of the bus network and established the principles for future network changes in subsequent light rail corridors.

Multidestination Network

TriMet's route structure in the urban part of the first light rail corridor was restructured from a radial network of closely spaced, low-frequency routes focused on moving people to and from downtown during rush hours into a high-frequency grid network serving a variety of destinations every day of the week. Three new frequent north–south lines were put in place four years before light rail opened. They are part of the grid route network in higher density neighborhoods. Each of these three lines crossed the future light rail alignment at station locations. The benefits of this conversion were numerous. Overall travel times were reduced, travel between destinations outside of the downtown became easier, and riders spent less time waiting at bus stops.

One crucial difference between the high-frequency grid and the system that preceded it was a new approach to connections. Under the previous system's design, transfers for riders were avoided as much as possible. Many routes travelled circuitous paths between destinations while attempting to deliver as many passengers in one trip as possible. The new high-frequency grid is premised on the fact that many passengers would willingly walk farther to and transfer between lines that provided more frequent and direct service. Frequency is the key to high ridership, as it outweighs the inconvenience of the longer walks and transfers experienced by some customers. Riders prefer making trips without connections, but the grid exchanges that convenience for more frequent service to a wider range of locations, which ultimately reduces trip times for most riders. As will be shown below, this high-frequency bus grid also acts as a force multiplier for rail.

Each new rail line replaced a high-frequency trunk bus line linking destinations along the corridor. In the years preceding the opening of a new rail line, service improvements are made on the trunk line and to routes that connect with the trunk. Riders attracted by this bus service are a built-in base of customers that can switch to the light rail line on completion, ensuring a high level of rail ridership and effectively using the higher capacity of the rail line compared to buses.

With proper planning, the effects of a light rail line can be expanded beyond the half-mile walk shed around stations and can reduce dependence on parking to access the line. Redesigning the bus network around the new rail line multiplies and extends benefits to the entire corridor. Bus lines replaced by light rail can be reallocated to provide more crosstown and local service that connects with light rail for longer trips. Ideally, the new rail service is in addition to the level of bus service formerly provided in the corridor.

Optimal Route Design

Designing the transit network around a rail line affords a great opportunity to seek out network efficiencies, harnessing the economy-of-scale power of light rail and taking advantage of its role as a high-frequency, high-capacity trunk line. Overlapping service can be reallocated or reduced as much as practical. This can be difficult due to public apprehension, but system and ridership benefits are commensurate with that difficulty. When TriMet's first light rail line opened on Portland's east side, it replaced several bus lines, including one that operated along the same arterial as the light rail and two park-and-ride expresses that ran on the freeway adjacent to the rail alignment.

Reallocating service that duplicates light rail provides more local service benefits for people who ride the new rail line by providing them with more and faster connections. The rearrangements also help bus riders along these more frequent and direct routes, enlarging the base of people who benefit from the new rail line. Reallocated service also can be used to expand service coverage or provide more direct connections between major destinations.

These changes also can reduce the impact of heavy bus volumes converging on a transit center in an area planned for high-density residential or mixed use development. In 2001 TriMet used the construction of the line to the airport to reconfigure the bus network in the corridor. The city of Portland was looking to jumpstart transit-oriented development in the city's only regional center, the Gateway Transit Center, a feature in the 2040 regional plan. Gateway was a major transit center that connected the eastside light rail line with 11 local bus lines, many of them with timed transfer connections. Developers indicated that heavy bus volumes were causing traffic concerns and creating noise pollution that could deter development. In response, TriMet used the construction of the airport branch as an impetus to reconfigure service. Timed transfer feeder routes in the area were replaced with a local high-frequency grid. This reduced volumes of bus traffic at Gateway Transit Center from 11 to five bus lines and strengthened the transit network in this developing area.

In cases such as the Gateway Transit Center, new light rail lines provide an opportunity to undertake network restructurings that otherwise would not be feasible. It is important to secure broad public and stakeholder buy-in for the concept by highlighting the benefits of the multimodal network before discussing specific route changes. Nevertheless, transit agencies may see resistance to such changes from some users of the existing system who understandably can be concerned that their service will be changed. The best way to address this apprehension is to place emphasis on the inherent benefits of the new light rail line, including its offer of faster, more reliable, smoother, and more spacious service than buses. Other persuasive statements include highlighting planned improvements to bus connections and improved access for pedestrians and bicyclists to light rail stations, stressing the fact that light rail frees up bus service that can instead be used to improve local travel options.

Light rail expansion onto the transit mall in downtown Portland provides an object lesson in how transit agencies can use light rail as a replacement for buses on street segments with multiple bus routes. Prior to 2009, bus service on the downtown transit mall posed challenges for both TriMet operations and adjacent businesses. The volume of downtown buses converging on this location exceeded capacity during the peak of the rush hour, even with two bus-only lanes in each direction of travel. The noise and crowding reportedly hampered business activity for storeowners and suppressed redevelopment potential along the mall's block faces.

In response, TriMet added light rail to the mall (by rerouting the existing Yellow Line and sending the new Green Line into the mall) and reconfigured the downtown parts of several bus lines to provide cross-mall connections perpendicular to light rail. This action reduced the volume of buses on the mall and shortened the distance of routes within the downtown. The resulting operational cost savings addressed a shortfall in operating funds. The design also strengthened the micro-grid of north–south and east–west service in the downtown.

Integrated Fares and Service

Barriers to connections are antithetical to the purpose of using light rail as the backbone or spine of service. Free connections between rail and bus are essential to encourage riders to take full advantage of the opportunities afforded by an integrated system. Passengers should not be charged extra for the privilege of transferring because connections require time and effort and increase the risk that a system delay will result in a late arrival. In balancing passenger revenue with ridership, especially in a multidestinational network, it seems unlikely that transfer fees can justify their chilling effects.

TriMet has a common fare structure for light rail and buses. There is no charge for transfers. The basic fare is $2.50 for 2.5 h on the system—trips in any direction on any fixed route service. This encourages short trips and is attractive for nonwork and school trips for which a round trip can be completed in the allotted time. The fare is relatively high by national standards, but it allows for short round trips to be made with one fare payment, creates less ambiguity for riders and the operators who must validate the fares, and reduces friction during connections. For a multimodal system with a high rate of connections like TriMet, this works well for both riders and the transit agency. Riders making two or more trips each day are encouraged to buy a $5.00 all-day pass on buses or from wayside ticket machines. This prevalidated fare instrument allows for faster boarding on subsequent trips by eliminating one of the cash transactions on buses and the need to queue up at a ticket machine to buy a return fare on light rail.

PARTNERS IN LAND USE AND TRANSPORTATION

High transit ridership depends in large part on local jurisdictions' land use and transportation policies, plans, and implementation mechanisms. TriMet does not control land use or the design of public rights-of-way, so the agency works in partnership with jurisdictions to find common ground on how transit can help achieve their goals and aspirations. These planning processes shaped the development of Portland's rail system and, for its part, TriMet changed the way it designed transit lines in response to them.

Transit network development and the local plans mutually support each other. When transit agencies and local governments are united in their efforts, they reap numerous benefits. Funds for construction and operations can be pooled to produce economies of scale; officials, agencies, and projects enjoy a broader base of political and public support; and access to federal/state funds for transit, pedestrian, and bike connections and transit-oriented community development is increased. Officials in local governments have investments in transit and benefit when transit proves successful. By cultivating relationships with local governments, transit agencies can build working partnerships. This means investing the transit agency's staff time and resources to be an active participant in a jurisdiction's planning process, advocating for the role of transit in shaping communities and explaining the basis for high transit ridership and effective operations. The key is to focus transit as a means to an end, a tool that will help communities grow and change in the way that they want to grow and change. Transit agencies should welcome plans that call for more transit than is presently affordable and advocate for additional operational funding in pursuit of realizing those plans.

Four Milestones

Oregon's statewide 1973 land use planning law was the antecedent for transit-oriented land use coordination in the state's largest urban region. The law requires comprehensive land use plans, with zoning based on those plans; statewide planning goals; urban growth boundaries; and a policy-making body to enforce and update the requirements. Subsequent planning and regulatory milestones that over the decades have shaped the development and success of Portland's light rail and bus network include the City of Portland's Downtown Portland Parking and Circulation Policy (1974) and Central City Transportation Management Plan (1995); Metro regional government's Region 2040 Plan (1992); the state's Transportation Planning Rule (1991); and the Oregon Environmental Quality Commission's Employee Commute Options Rule (1996).

Transit is the preferred means of access in the Downtown Parking and Circulation Policy. The Portland Transit Mall—originally serving only buses and now a multimodal facility with bus and light rail service—established the policy and practice of giving transit priority access to the high density areas and designing streets that favor transit and pedestrians instead of auto traffic. The presence of the transit mall also serves to increase the brand awareness and image of transit as a viable alternative to driving and parking downtown.

TriMet was a key player in preparing the Central City Transportation Management Plan, adopted nine years after the first light rail line opened. This plan increased density near transit, raised requirements for transit- and pedestrian-oriented development features, and restricted automobile parking. It also expanded these requirements to areas adjacent to the traditional downtown, including the Lloyd District, located across the Willamette River from downtown along the eastside line. Lloyd District is now traversed by a light rail spine with three light rail lines operating at combined 5-min headways throughout the day, every day of the week. Lloyd District employment increased from about 15,000 to 23,000 between 1994 and 2015. Transit modal split for work trips increased from 10% in 1994 to 20% in 2013, while 37% of employees on subsidized passes commute by transit (*3*). The increases are attributable to the new light rail and bus service, paid on-street parking at formerly free spaces, maximum parking ratios, and deeply discounted transit passes.

The Portland region, through its regional government, Metro, has a history of coordinating land use and transportation investments. Metro's policy for increasing capacity prioritizes transit and other active transportation modes over highways. Integrated transportation and land use planning was a tenet of the Region 2040 Plan, which was undertaken as planning and design of TriMet's westside line to Hillsboro was underway. The process simultaneously evaluated land use and transportation alternatives. Metro had the legal authority and political will to move ahead with implementation by requiring local governments to change their plans and zoning to be consistent with the regional plan and to use transportation investments to shape land use (*4*).

Oregon's Transportation Planning Rule, adopted about the same time as the 2040 Plan, strengthens efforts to encourage compact, mixed-use, pedestrian-friendly development around light rail transit (*5*). The city of Gresham, at the eastside terminus of the light rail line, advocated for the rule. This was due in part to the fact that Gresham was the first Portland suburb to realize direct benefits from light rail (*6*).

The Employee Commute Options Rule was timely, in that light rail opened on Portland's west side two years later through a corridor with many large employers and rapid employment growth. TriMet was in the midst of outreach to employers and to the public about the redesign of service on the west side. Large employers were required to reduce commute trips by 10% within three years and to offer incentives for employees to commute to work via alternate modes of transportation. As shown later in this paper, this created a major opportunity for TriMet's marketing efforts to develop ridership on the region's west side.

Station Area and Corridor Land Use Planning

During the development of the first light rail line in the 1980s, station area planning was hampered by an ongoing recession. The rail line was built with a focus on improving service, but the germ of ideas for fostering economic development in station areas was planted through a transit station area planning program. The full potential of light rail to shape development was realized a decade later when light rail was extended on the west side. TriMet rode the crest of the economic boom in the 1990s, buoyed with new government policies that supported transit. The extension west from downtown Portland was built through a corridor with much undeveloped land that was attractive for development. The west side had 1,500 acres of vacant, developable land along the rail line, roughly three times that of the eastside corridor (*7*). The corridor was dubbed the Silicon Forest because many high-tech firms located and expanded there.

Corridorwide land use planning started even before preliminary engineering on the rail line. Light rail was recognized by politicians and policymakers as a key tool for shaping growth. FTA approval of New Starts funding for the Hillsboro segment of the westside line was contingent on the enactment of and local compliance with Metro's Region 2040 Plan, adoption of local station area plans to support increased ridership, and adoption of policies to meet the Oregon Transportation Planning Rule.

STATION ACCESS AND DESIGN

Portland's light rail lines run on a variety of alignments—alongside freeways, in arterial medians, in reserved lanes on city streets, and within exclusive rights of way. Station placement along the alignment and access to those stations is influenced by many factors, including land use, pedestrian connections, operating speeds, intermodal connections, land availability, and adjacent roadways. TriMet puts emphasis on pedestrian access to stations and encourages high quality design for the streetscape and development adjacent to station platforms.

Competing demands for use of land immediately adjacent to stations can require tradeoffs and compromises, particularly with regard to mode of access. One of the challenges is to demonstrate to developers and local land use planners that bus service is an asset, not a liability. Bus stops and facilities are located and designed to be compatible with adjacent development. Connecting bus facilities are designed with the same quality and amenities as the rail platforms. Bus stops are cleaned and maintained to the same standards as the rail platforms.

A large transit center occupies land that otherwise would be available for transit-oriented development. It can also add to perceptions of traffic, noise, and pollution to the station area. In some cases limiting the concentration of bus traffic at a transit center can be achieved by increasing frequencies and transitioning from a timed-transfer to a grid network structure, as TriMet did in the Gateway area. If the pedestrian environment is good, short walks are acceptable for passengers transferring between frequent services. This means that good pedestrian infrastructure and frequent service does more than help riders—it lets transit agencies be more flexible and responsive to multiple needs in their station area designs.

Park-and-ride lots consume valuable space and create a less-than-pleasant pedestrian experience, which can suppress the demand for adjacent development and active transportation access to stations. Locating parking a short walk from the platform or building parking structures, while more expensive to construct and operate, are ways to balance these challenges.

In line with TriMet's Complete Trip concept, the agency's plans account for the fact that a rider's experience before and after setting foot on a TriMet vehicle is just as important in modal choice as the vehicle trip itself. After all, a large proportion of time on a short trip might be spent waiting for a bus or train to arrive and travelling to/from a stop. To that end TriMet emphasizes safe, welcoming, and modern station design; ongoing maintenance and cleaning; short connections (time and distance) between buses and rail; and easy pedestrian and bike access to adjacent developments.

Streetscape

A high-quality streetscape along major transit lines, whether rail or bus, is an important ingredient to successful ridership development. It signals to developers, building owners, and tenants that there is a permanence and commitment to the service and passenger facilities. It also shows stewardship in maintenance and operation of the street by the local jurisdiction and TriMet. As a result, transit becomes a more viable option for trips by providing a safe, attractive, and welcoming station area environment.

This philosophy was a component of the success of Portland's first rail line. In 1983 a local improvement district was approved by businesses to build a better streetscape on the nonrail side of the streets along the downtown Portland alignment. It rebuilt 34 blocks of downtown streets and sidewalks to a high level of quality. This included brick and granite street intersections, granite curbs, planters, and art on brick sidewalks widened to 18 ft.

Introducing light rail into dense, built-up areas provides excellent ridership potential and can take pressure off of the bus system by replacing high-ridership bus lines. It also brings challenges. Transit agencies can face tight quarters, heavy multimodal traffic, and high expectations from the public and local business owners. TriMet's construction of light rail on the downtown Portland Transit Mall in 2009 faced all of these challenges.

The transit mall was opened in 1978 as a bus facility along a couplet of one-way streets. By 2006 the amount of bus traffic and the results of years of deferred maintenance had compromised the mall's attractiveness for riders, pedestrians and businesses. The planned introduction of light rail along the mall, coupled with extension of the mall to span the entire downtown, would alleviate bus congestion and bring more activity to the streets. It also provided the opportunity to improve the pedestrian and station area infrastructure and to update street furnishings. To that end, in 2009 TriMet partnered with the city of Portland, Metro, and downtown businesses to renovate 58 blocks and enhanced sidewalks with 45 new transit shelters. In recognition of the community's high expectations, TriMet contracted with an urban designer to lead an interdisciplinary design, construction, and operations team (*8*). Cleaning, security, and general maintenance along the mall are handled by an independent nonprofit to ensure that the streetscape will be well maintained in the future.

The introduction of light rail onto the mall, running perpendicular to the original downtown rail alignment, proved to be operationally challenging. There are two transit-exclusive lanes for buses and rail to share. Even after taking out buses that duplicated rail service there were still many vehicles to fit into these two lanes. If the rail line were in the right-hand lane, it would be blocked by buses servicing their stops on the right-hand side. If it were in the center, island platforms would be required between the auto lane and the rail lane, resulting in less-than-welcoming waiting environment, compromised sidewalk widths, and safety concerns.

The solution is to put rail in the left lane and place stations on the right side of the street, which already had wider sidewalks to accommodate the original bus stops on the mall. Tracks weave from the left-hand lane to the right in order to serve stations roughly every five blocks, or a quarter mile. Lane changes for buses and trains are controlled by regular traffic signals at intersections. This required downtown stations to be set roughly twice as far apart as on the original rail line, but TriMet found that this spacing is better than on the first downtown alignment. It allowed for faster operating speeds and smoother rides for customers, especially for those passing through downtown.

Pedestrian Access

Almost every transit rider is a pedestrian at some point in his or her trip. Therefore, TriMet places priority on partnering with jurisdictions to improve pedestrian access to transit and increase street connectivity. Local jurisdictions take lead responsibility for pedestrian access, while TriMet and the metropolitan government have completed pedestrian inventories and needs analyses, advocated for use of flexible federal funds to improve the pedestrian environment, and partnered with jurisdictions and interest groups on improving pedestrian safety and access for people with disabilities.

The region's first pedestrian-to-transit program was initiated by the city of Gresham in 1994 (*9*). The eastern half of the first light rail line was characterized by lack of sidewalks and discontinuous street network. The Ped-to-MAX program (TriMet's light rail system is named Metropolitan Area Express, or MAX) encourages transit ridership by redesigning streets and constructing pedestrian enhancements.

Construction of the Yellow Line in the early 2000s through an urban renewal area in North Portland had more public support and a history of successful rail projects behind it. Planning for pedestrian infrastructure was incorporated into the service planning process early on. This included coordination with the city of Portland to provide hundreds of accessible curb ramps, install pedestrian crossings and improvements, and fill gaps in sidewalk connections to bus stops and light rail stations.

The success of this pedestrian focus along the Interstate Avenue corridor, coupled with broader eligibility of access improvements for federal funding in 2011, led to substantial bike and pedestrian investments in the current construction of the Orange Line through southeast Portland to Milwaukie (*10*). TriMet invested $34 million dollars in pedestrian and bike infrastructure. TriMet made this investment for pedestrians and cyclists in line with its Complete Trip philosophy of service planning, along with lessons learned on previous lines around the importance of an attractive "first and last mile" to strong ridership.

Bus Access

Bus–rail connections benefit from short, accessible, attractive pathways between bus stops and light rail stations. Several westside stations were located away from arterials on which buses operate in order to take greater advantage of the stations' land development potential. Buses deviate off route to serve several of these stations. Some street network geometries were designed to preclude buses because in some cases developers and urban designers did not view bus service as an asset. Concerns included noise and pollution, as well as impact of buses on street widths and adjacent development.

Transit agencies need to be flexible about designing their stations to fit with the local land use and urban design context. TriMet's Green Line terminates at Clackamas Town Center, a regional center. Initial plans called for 20-bay transit center and a park-and-ride garage. The owners of the mall and county planners had concerns about size of the transit center's footprint in an area planned for higher density development. TriMet redesigned it so that buses lay over in a secure area on the first floor of the garage. Two bus stops with amenities replaced the original, more space-consumptive sawtooth design and were located closer to the rail platform than would have been possible with that design.

Convenient on-street bus–rail connections in high-density station areas require that bus stops are close to and visible from the rail platforms and that passenger facilities at bus stops are visually and psychologically connected to the platforms. At Yellow Line stations that connect with frequent crosstown bus lines, TriMet built bus stops to the same design standards as the adjacent rail stations. In addition to accentuating connectivity to the rail line, these enhanced bus platforms communicate the permanence of the stop and service as well as TriMet's commitment to high quality design and maintenance of stops adjacent to high density residential developments.

Operational Needs

Operational needs should be articulated early and persistently during the conceptual design and preliminary engineering phases. Nevertheless, operations staff need to be creative and flexible in balancing their needs with other priorities for the station areas. Providing bus connections close to rail stations is essential, and these facilities should be part of the scope of the rail project. Bus layover locations and capacity needs also should be addressed early in the project scope.

Operations staff members are in the best position to make judgments about lane width, turning radii, and operator facilities, so including them early in the planning process is essential to a successful project. Field testing the dimensions of a proposed roadway or transit center design by laying out those dimensions in a bus yard or parking lot, test-driving the layout, and making needed adjustments before final design can save time and money down the road.

MARKETING

Marketing has been important to the success of transit in Portland because it is an integral part of an overall transit development strategy. New light rail projects, because of their visibility and quantum jump in service levels, offer a rare opportunity to leverage marketing partnerships with employers, jurisdictions, and other stakeholder groups.

Employer Programs

Transit agencies can benefit by focusing marketing attention on large employers. The westside was a hotbed for employment growth in the '90s. Access to these suburban jobs was an important issue, including reverse commuting from Portland. TriMet created a universal pass program for employers that was adopted by most of the big employers in the corridor. An employer buys a pass for every employee at a worksite, paying an affordable annual fee to TriMet based on current levels of transit use by employees at the worksite. When the westside line opened in 1998, about 50,000 employees at 86 employers had enrolled, providing $1.5

million in revenue. Today, the program enrolls 215 annual accounts and generates $16 million per year.

TriMet also committed substantial staff resources to developing partnership plans with large employers in the westside corridor. Reconfiguration of the former radial bus service to nondowntown, intracorridor alignments meant that many of these employers would benefit from more direct and frequent service in areas where most of their employees live. Staff worked with employers to map home locations of their employees, the majority of whom would be served by the reconfigured intrasuburban bus routes made possible by reallocation of former radial lines replaced by light rail.

To supplement fixed-route service, TriMet develops last-mile connections with subsidized vanpool shuttles, provided by a third-party vendor, between stations and worksites not served by local routes. TriMet also encourages employer shuttles into transit stations and centers, along with bike share and car share programs. TriMet provides secure bike parking at many stations and partners with employers and jurisdictions to plan and fund pedestrian and bicycle last-mile improvements.

Multimodal Marketing

The first large-scale TravelSmart project in the United States was part of service planning for the Interstate Avenue light rail corridor. It included a multimodal first/last-mile approach and emphasis on partnerships (*11*). The project identified individuals who would like to make more use of alternate forms of transportation and provided them with the information and tools they need to transition away from automobile trips. It reached over 14,000 people in corridor. Transit ridership increased when transit system improvements were coupled with individualized marketing: While transit trips increased 24% due to service improvements, they increased 44% in the TravelSmart area. This suggests that individualized marketing may be a useful tool for other transit agencies seeking to attract potential riders to new and existing service.

CONCLUSIONS

Portland's three decades of experience in operating an integrated rail–bus transit system resulted in real, measurable success, according to the two yardsticks on which it places the most emphasis: ridership and public approval. TriMet's overarching approach to light rail development is to embrace transit as a means to an end—to serve communities' needs and to help them grow and pursue their aspirations. The design and operation of TriMet's facilities and service reflect the communities they serve. TriMet achieves this by adhering to a Complete Trip philosophy that addresses not just the transit service itself, but also land use, street design, and customer information and marketing. This requires partnerships with jurisdictions, employers, and interest groups to leverage the most benefits from each new rail line and to extend them to a broader audience. TriMet's project design and operations are responsive to community context, leverage opportunities for innovation, and accentuate modern high-quality design.

This paper concludes by reiterating and making explicit some of the discoveries and philosophies that TriMet has developed over the past 30 years. Other transit agencies can adapt these lessons learned to their regions and systems.

Service Planning

- Light rail is most useful when ridership is a transit agency's principal goal and priorities flow from the overarching goal of increasing ridership.
- Light rail achieves high ridership when it is integrated with a high-quality bus network that supports convenient connections between modes.
- New rail lines, due to their public visibility and management's interest in ensuring a successful startup, can be an opportunity for transit agencies to innovate with aspects of their service, even during lean budget years.
- Public support for network restructuring is best built by engaging the community and stakeholders early in the design and construction period. Public support can be nurtured by emphasizing the benefits of the new rail line and, equally important, describing how light rail allows reallocation of bus service to improve multidestinational travel opportunities.

Network Design

- Light rail is most successful when transit agencies build demand for transit by increasing service in the rail corridor during construction and then reallocating service replaced by the rail line to improve local and crosstown access.
- Frequency is the most crucial aspect of service design. High frequency allows for passengers to make spontaneous trips and easy connections between light rail trains and buses.
- Once a rail line is opened, transit agencies can look at removing redundant service and using the savings to create rail-supportive bus service, expand service coverage or, in lean times, address budget shortfalls.

Land Use

- By partnering with local governments to develop station area and corridorwide land use plans, transit agencies can encourage transit-oriented communities early in the design process.
- The limited space around stations requires balancing transit-oriented development with the operational and facility needs of transit service. Being innovative and flexible and providing capital funding for integral bus improvements helps transit agencies ensure success of a rail project.
- When transit planners consider the operational needs of service early on in the design of a new rail line, they are easier to accommodate. Examples include location of connecting bus stops, layover locations, and operator break room facilities.
- Planning never stops. Once a rail line has been open for a few years, it is time to revisit the corridor and re-evaluate service and facilities to respond to changing travel patterns, operational needs and to keep facilities modern and operationally efficient.

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Importance of Bus Connections to Light Rail Accessibility Gains

ANDREW GUTHRIE
YINGLING FAN
DAVID M. LEVINSON
University of Minnesota

The research explored whether light rail and associated bus service changes soften the impacts of spatial mismatch in the region by improving transit employment accessibility. Specifically, researchers set out to answer the following questions: (1) To what degree the implementation of light rail and associated bus service changes led to changes in transit employment accessibility? (2) How do accessibility changes differ for high- and low-wage workers? and (3) Are jobs and/or workers relocating to take advantage of light rail and bus connections? Researchers produced systemwide, 30-min cumulative opportunity employment accessibility calculations for the region before and after light rail implementation. They then estimated ordinary least squares regression models to explain accessibility changes to low-, medium-, and high-wage jobs as a function of location in light rail station areas and along bus routes offering a direct connection, as well as social and built environment control variables. Following the accessibility analysis, researchers also modeled net change in commute flows for commutes between transit-served origins and destinations to explore workers' and employers' location decisions following light rail implementation. Researchers found effective integration with a fine-grained network of local bus connections crucial to the success of light rail. Implications for light rail planning practice are discussed.

INTRODUCTION

Light rail transit can dramatically improve transit travel times in specific corridors. This increase in mobility can, in turn, dramatically expand destinations reachable within a reasonable time, increasing station-area accessibility. By providing rapid, reliable, regional transit mobility, light rail investments can also alleviate problems of spatial mismatch for transportation-disadvantaged workers. Despite these benefits, light rail directly serves a relatively small number of locations—limited stops are a key part of how light rail shortens travel times. This fact unavoidably restricts numbers of potential transit users within walking distance of stations. Light rail lines also represent major public investments, funded primarily by taxes collected outside station areas. In addition, the desirability of light rail access tends to raise station-area property values and attract intense, market-rate development, potentially making it difficult for transit-dependent people—who stand to benefit the most from improved transit—to live within walking distance of light rail. These reasons of efficiency, fairness, and social justice demand that access modes other than walking be effectively provided for in the implementation of light rail.

Park-and-ride facilities play a valuable role in expanding geographic access to many right rail lines, but do not represent a sufficient solution in and of themselves: park-and-ride facilities require a great deal of land relative to the ridership they attract (making them inefficient solutions in urban neighborhoods), they hamper opportunities for transit-oriented development, and they do little to improve rail access for transit users who do not own a car. Local bus connections can offer an effective access mode for light rail stations, particularly in urban areas, but there is no guarantee that they will following the implementation of a new light rail line. The narrative of rail investments cannibalizing funding for bus service is a well-known one, and not entirely the product of political propaganda. Light rail lines often follow highways or railroad alignments (as opposed to existing bus routes) to simplify their construction. Bus-only transit systems also tend to be organized nonhierarchically, optimized for passengers to remain on a single bus for as much of their trip as possible, rather than transfer from locally focused feeder routes to regionally focused line-haul services.

In light of the need for effective bus connections to light rail lines and the potential obstacles to their realization, this paper explores the role of bus connections in the regional employment accessibility impacts of the implementation of the Twin Cities' Metro Blue Line. Specifically: How do employment accessibility gains along connecting bus routes compare to gains in station areas? How do those employment accessibility impacts differ for high- and low-wage workers? Are workers and/or jobs relocating to take advantage of accessibility gains?

Study Area

This paper focuses on the Metro Blue Line (formerly known as the Hiawatha Line) in the Twin Cities of Minneapolis–Saint Paul, Minnesota. The Blue Line opened in 2004 and was the region's first rail transit line since the abandonment of streetcar service half a century earlier. In downtown Minneapolis, the line employs dedicated-lane street running; through the neighborhood of South Minneapolis, it follows mainly railroad and highway alignments before tunneling under MSP International Airport and proceeding to the Mall of America in suburban Bloomington in a mix of median and greenfield alignments. This basic form is common among recently implemented light rail lines in the United States and is not ideal for pedestrian and community connections to stations (*1*).

The Blue Line passes through Minneapolis residential neighborhoods in which significant numbers of low-wage workers live and offers direct service to downtown Minneapolis as well as the major suburban employment centers of MSP Airport and the Mall of America. Figure 1 shows the distribution of low-wage workers and low-wage jobs (used as a proxy for jobs for which the working poor are most likely to be qualified) in the Twin Cities region prior to light rail implementation, based on the Census Bureau's Longitudinal Employer and Household Dynamics (LEHD) database. This map demonstrates the prevalence of spatial mismatch in the region, with low-wage workers concentrated in the inner cities, and the heaviest concentrations of low-wage jobs concentrated in suburban centers (*2*, *3*). Additionally, the broad distribution of low-wage workers within the inner cities underscores the need for effective bus connections if significant numbers of low-wage workers are to benefit from light rail.

At first glance, bus connections appear to play a critical role in light rail access: Over half of all light rail passengers transfer from and/or to a bus on at least one end of their rail trip (*4*). Such a finding does not establish, however, whether realized bus–rail trips actually represent an improvement over previous bus trips. Indeed, forced transfers are a common complaint surrounding the development of rail transit, frequently mentioned in arguments that rail development hurts existing transit-dependent bus riders. While concerning, such arguments tend to proceed from anecdotal evidence and/or consider added transfers a negative outcome without

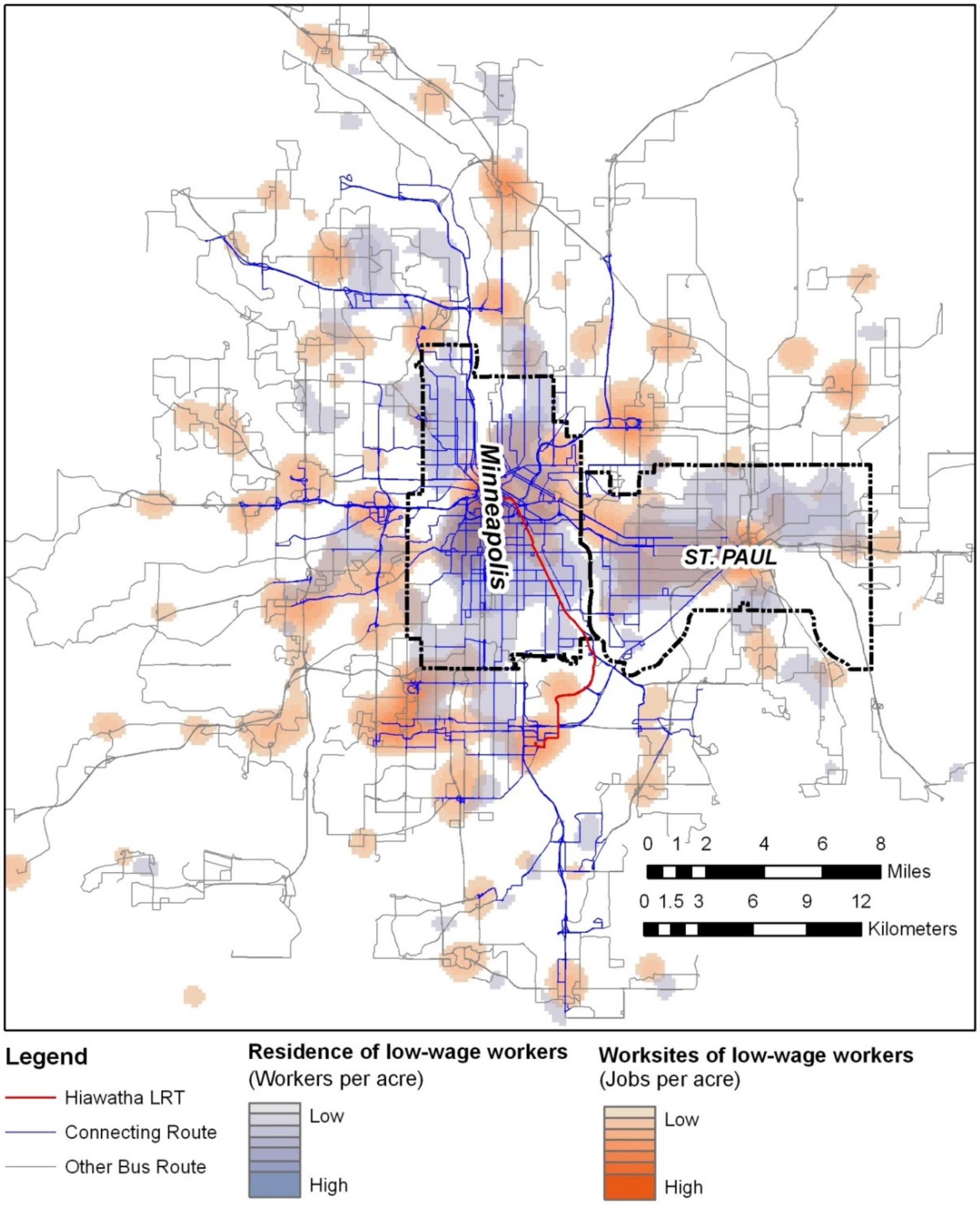

FIGURE 1 Locations of low-wage workers and jobs before implementation of light rail and connecting bus routes.

analyzing mobility or accessibility impacts (*5*, *6*). This research offers a systematic, empirical evaluation of the impacts of light rail implementation and associated bus service changes on what one can accomplish with transit travel through the use of cumulative opportunity accessibility analysis.

LITERATURE REVIEW

Despite the recent resurgence of rail transit, the United States is still predominantly a bus transit nation. While rail lines often attract ridership out of all proportion to their length and number, bus routes remain overwhelmingly dominant in terms of geographic coverage (*7*). Transit users are frequently willing to walk somewhat farther to reach rail stations than bus stops, but even this increased catchment area is insufficient for rail to equal the direct service coverage of bus systems (*4*, *8*). In addition, modern-day rail lines require achieving ridership levels much greater than they reasonably may relying on station-area residents and destinations alone: In an international analysis of factors contributing to the success (or lack thereof) of recently built rail transit systems, Babalik-Sutcliffe found convenient integration with bus service to be a key factor in the success of every rail system she classified as successful (*9*). Kuby et al. found a strong positive relationship between connecting bus routes and light rail boardings at 268 stations located in nine regions across the United States (*10*). Currie and Loader also found that bus–rail transfers are important and that transferring is facilitated by frequent, easily understood services, like rail lines (*11*).

Increased ridership is a desired outcome from the perspective of transit providers (*12*). From the perspective of individual transit users, however, a ridership gain hints at positive outcomes (assuming users behave more or less rationally) but is not an outcome at all in itself. (Individual users likely care more about what they themselves can accomplish by using transit than about how many of their neighbors use transit along with them.) A much more reasonable outcome measure from the perspective of transit users is cumulative opportunity accessibility, that is, the total number of desirable destinations (most commonly jobs) they can reach via transit in a given amount of time (*13*). In fact, transit job accessibility strongly predicts transit mode-share (*14*).

In previous research on the Twin Cities' Metro Blue Line, Fan et al. found "that proximity to light rail stations and bus stops offering direct rail connections are associated with large, statistically significant gains in accessibility to low-wage jobs," and that "These gains stand out from changes in accessibility for the transit system as a whole" (*15*). This paper refines that analysis by examining specific bus route changes in the context of accessibility gains and losses.

ACCESSIBILITY ANALYSIS

The research employed the cumulative opportunity approach to calculate block-level transit job accessibility, with a 30-min cutoff time. As such, the accessibility calculation is a count of the total number of jobs reachable within 30 min by a walk-and-ride transit trip, allowing for access/egress walking time, waiting time, and in-vehicle time. To simplify processing, a maximum of one transfer is allowed. Blocks more than ¼ mi (400 m) from a transit stop are excluded. To account for changes in transit service throughout the day, the analysis uses a weighted average accessibility index considering every weekday hour from 5:00 a.m. to 9:00 p.m. based on the following equation:

$$\text{Weighted average accessibility index} = \bar{A}_{peak} \times P_{peak} + \bar{A}_{nonpeak} \times P_{nonpeak}$$

where

$\bar{A}_{peak}$ = the average accessibility of all peak hours;
$\bar{A}_{nonpeak}$ = the average accessibility of all off-peak hours;
P_{peak} = the percentage of transit trips made within all peak hours; and
$P_{nonpeak}$ = the percentage of transit trips made within all off-peak hours.

P_{peak} and $P_{nonpeak}$ are calculated using a 2006 on-board survey of transit riders conducted by Metro Transit (*16*). (Based on the times Twin Cities transit providers charge peak and off-peak fares, the hours from 6:00 to 9:00 a.m. and 3:00 to 6:00 p.m. are considered peak hours; all other hours are off-peak.) Separate accessibility calculations describe accessibility to low-wage (<$1,440/month), medium-wage ($1,440–$3,399/month), and high-wage jobs (≥$3,400/month).

Map Analysis and Bus Service Changes

Figure 2 shows absolute low-wage job accessibility before light rail implementation (using the 2000 transit network and 2002 LEHD data) and after implementation (using the 2005 transit network and 2006 LEHD data), as well as the change in low-wage job accessibility between the two. Warmer, more intense colors indicate higher accessibility/greater gains. The area of South Minneapolis served by the Metro Blue Line experience significant gains in transit low-wage job accessibility after implementation. This should come as no surprise in station areas themselves, but note that the gains extend well beyond immediate station areas [defined, as with all other stops, based on a ¼-mi (400-m) radius] along bus routes that connect with light rail.

Most of the Twin Cities transit system offered improved low-wage job accessibility in 2005 as compared with 2000. These improvements are not universal, however, and some departures from the trend occur in unexpected places such as near the light rail line or in areas with high absolute transit accessibility. In addition to the construction of the Hiawatha light rail transit (LRT) line, the Metropolitan Council and transit providers undertook a significant restructuring of the bus system. Some changes in this restructuring were made to integrate the new light rail line with the regional transit system; these changes include realigning routes to provide feeder/distributor services for LRT and discontinuing sections of routes that would duplicate LRT service. Others were been reconfigured for other reasons. (Most Saint Paul route changes, for example, likely have little to do with light rail.) Some transit accessibility changes seem easily explainable by service changes, while others are likely related to job locations. Table 1 summarizes changes in routes offering South Minneapolis connections to light rail. (Note: Metro Transit changed its route numbering system between 2000 and 2005; old numbers are shown in parentheses where they differ significantly from new numbers.)

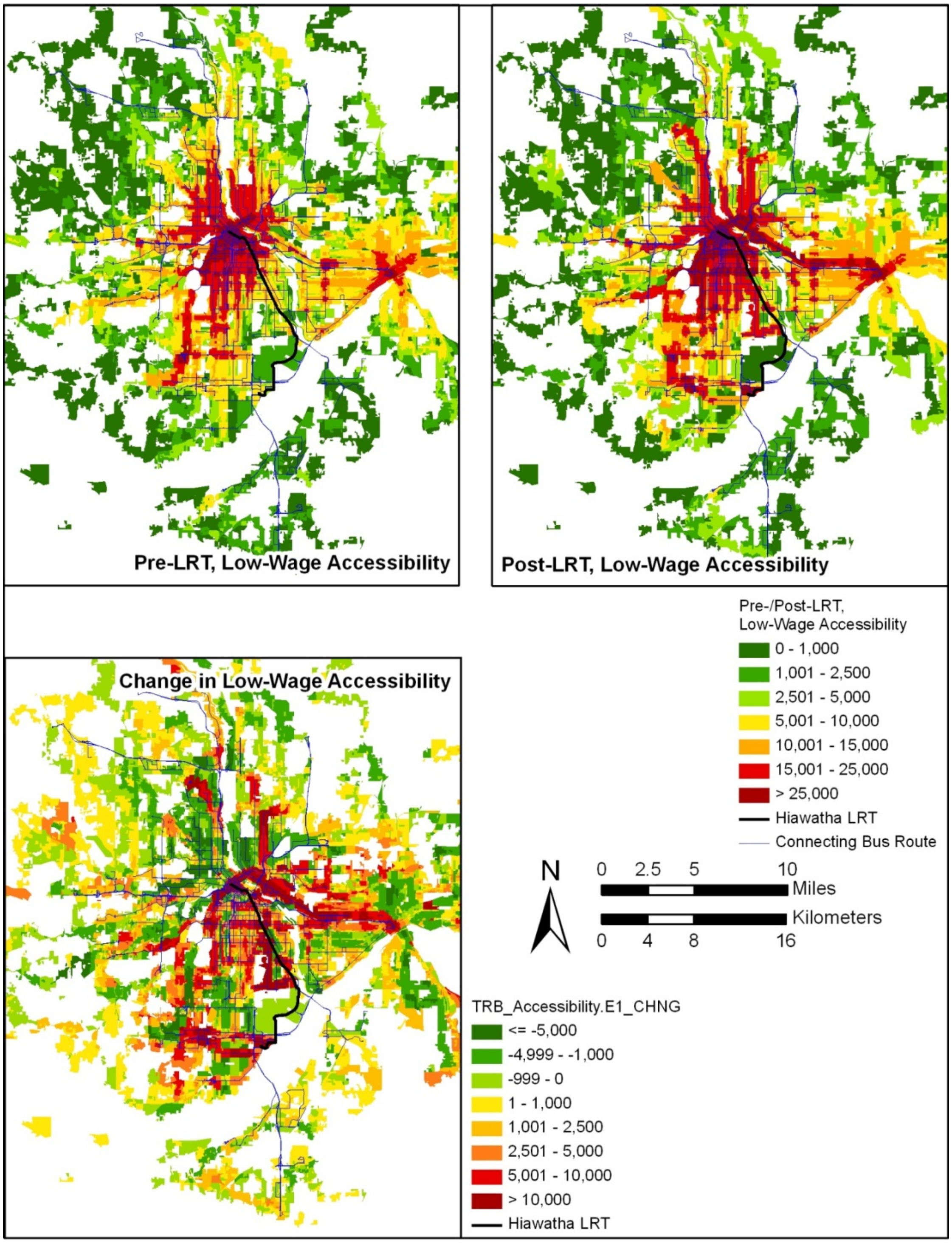

FIGURE 2 Transit accessibility to low-wage jobs, pre- and postimplementation.

TABLE 1 Bus Service and Accessibility Changes

Gain/ Loss (+/–)	Area	Service Changes
+	28th Ave. S	Downtown via Hiawatha branch of 19 discontinued; southern terminus moved to Va. from MOA; large accessibility gains in spite of forced transfers.
–	Minnehaha Ave., south of 38th St.	7 discontinued south of 38th St. station; previous terminus was MOA (7 restored on Minnehaha after 2005). Served by 27, but lower frequency and no downtown service.
+	Hiawatha Ave., north of 39th St.	Branches of 7, 19, and 22 discontinued. Route 20 completely eliminated. All bus service supplanted by LRT.
+	Bloomington Ave. S	14 rerouted to serve 38th St. station via 38th St. and 42nd St. Required significant back-tracking, but still yields significant accessibility gains.
+	Lake St.	Higher service frequency for 53 (M-191) limited-stop service; local route 21 takes a large frequency cut (the 21 is the bulk of transit service on Lake St.). LRT connection with 21 likely important.
+	38th St.	Increase in frequency for the 23 and addition of LRT connection.
+	46th St.	New cross-town Route 46 (some pre-LRT service provided by 22).
Mixed	Highland Park	74 (S-14) and 84 (S-4) rerouted to cross into Mpls and serve 46th St. station.
+	Cedar Ave. S (Eagan, Apple Valley)	442 discontinued north of MOA; no longer serves VA and Ft. Snelling. Accessibility gains despite forced LRT transfer @ MOA.
–	Bloomington Ave. S (Richfield)	Some 515 (M-15) trips re-routed off Bloomington Ave. via TH-77.
–	66th St.	Significant increase in service frequency for 515 (M-15). Reason for accessibility loss unclear.
Mixed	TH-13	444 discontinued north of MOA; no service to airport. Accessibility changes (positive and negative) are mixed together, with no apparent pattern relative to service changes.
+	Chicago Ave. S, Portland Ave. S (south of 60th St.)	Branch of 5 terminating at 62nd St. discontinued; more trips now serve MOA.
–	Nicollet Ave. S	Major frequency reduction for the 18.
–	44th St. S (west of Lake Calhoun)	44th St. branch of 6 (M-28) discontinued.
–	Franklin Ave., east of Riverside Ave.	8 discontinued west of Franklin Ave. LRT station (previously served downtown Minneapolis, continuing to Golden Valley). Large frequency reduction in addition to forced transfer.
+	University Ave.	Few changes to 16 and 50. LRT connection added and may play a role; appears unlikely to account for entire observed accessibility gain.
+	86th St. S (Bloomington)	New local route 539 added as Bloomington Edina Line LRT shuttle. No previous cross-town service.
+	Old Shakopee Rd. (Bloomington)	New local route 538 added as Bloomington Edina Line LRT shuttle. No previous crosstown service.
–	34th Ave. S near 50th St.	34th Ave. sections of 7 and 22 discontinued; partly replaced by 27, but with less direct route and much lower service frequency (7 restored on 34th Ave. after 2005).
+	S Minneapolis, east of Hiawatha Ave.	24 (M-20) rerouted so southern terminus is 46th St. station instead of Highland Park in Saint Paul.

Accessibility Regression Analysis

The map analysis provides fine-grained detail on the spatial relationships of accessibility changes to specific bus service changes and light rail connections. It does not, however, allow for separate consideration of the magnitudes of accessibility changes in station areas and along connecting bus routes, while holding other factors equal. Regression analysis allows for this separate consideration. Specifically, the authors estimated three ordinary-least-squares regression models to explain the change in accessibility to low-, medium-, and high-wage jobs as a function of location in LRT station areas (subdivided into downtown stations, the three northern urban neighborhood stations, the four southern urban neighborhood stations, and suburban stations) and connecting bus route areas [defined as within ¼ mi. (400 m) of stops served by bus routes offering a direct light rail connection, with time to travel to the rail station, wait the average peak waiting time and travel by light rail at least one stop within 30 min], as well as the distance to the nearest transit stop (regardless of service type) and surrounding social conditions.

Table 2 shows the results of the accessibility regression models. In all cases, location within a light rail station area or bus connection area is highly significant, with a positive coefficient. (Note: The coefficients are not comparable across models or key explanatory

TABLE 2 Accessibility Regression Results (Dependent variable = before–after change in number of jobs by type within 30 min by transit)

	Model 1 Low-Wage Jobs	Model 2 Medium-Wage Jobs	Model 3 High-Wage Jobs
Key Explanatory Variable			
Downtown LRT	14,259.031***	18,904.961***	19,663.491***
North LRT	8,282.851***	13,626.505***	22,698.052***
South LRT	11,652.523***	18,347.581***	37,933.302***
Suburb LRT	6,977.594***	11,405.500***	33,664.773***
Connection LRT	1,814.218***	3,294.392***	7,683.292***
Control Variables			
Pre-LRT low-wage job accessibility	–0.121***		
Pre-LRT medium-wage job accessibility		–0.208***	
Pre-LRT high-wage job accessibility			–0.110***
Dist. to nearest transit stop (100 ft)	–63.937***	–119.541***	–274.169***
High-frequency bus	2,506.573***	4,137.235***	6,957.125***
African American (%)	–24.503***	–36.409***	–26.345***
Latino (%)	15.812***	25.416***	73.204***
Asian (%)	8.501***	–2.728	–2.644
Single-parent family (%)	–25.448***	–35.211***	–28.377***
College degree (%)	57.257***	102.038***	138.706***
Owner occupied (%)	–5.959***	–11.665***	–17.696***
Zero-vehicle household (%)	17.630***	28.155***	62.096***
Median household income ($K)	–49.230***	–80.328***	–112.557***
Constant	2,653.180***	3,928.345***	6,328.680***
Summary Statistics			
Number of blocks	22,588	22,588	22,588
R^2	0.196	0.191	0.233
F-test (p-value)			

NOTE: $*p < 0.1$; $**p < 0.05$; $***p < 0.01$.

variables due to differing baseline accessibility values.) Table 3 shows the percentage change in job accessibility in station and bus connection areas. Connection areas have smaller accessibility increases than station areas, though it is important to consider this finding in the context of the considerably greater area (and number or workers) served by bus connections than served directly by light rail.

In bus connection areas, accessibility to low- and medium-wage jobs show significantly smaller gains than accessibility to high-wage jobs. This is not the case in either the downtown or north neighborhood station areas, where low-wage accessibility gains are greater than or roughly equal to medium- and high-wage accessibility gains.

Discussion of Accessibility Analysis

Based on the map analysis and the accessibility regressions, light rail station areas experience the most intense accessibility gains, while bus connection areas experience less-intense gains distributed over much greater areas. In fact, based on the small size of station areas, as well as their limited number, it seems quite clear that by far the greatest number of workers who potentially benefit from improved transit job accessibility due to light rail do not live in light rail station areas. Rather, they live along connecting bus routes. This conclusion may seem obvious, perhaps so much so as to appear anticlimactic. However, it represents a significant divergence from common, intuitive understanding of light rail's role in improving regional accessibility.

That the greatest aggregate effects of rail transit occur along connecting bus routes challenges traditional concepts of transit-oriented development (*17–19*): The common focus on relatively small quantities of very high-density mixed use development within prime walking distance of rail stations seems to ignore significant potential for greater quantities of more moderate-density residential and/or neighborhood commercial development catalyzed by convenient bus–rail connections. Such development would represent a significant shift in transit-oriented development planning but could dramatically increase the supply of land available for transit-oriented development (*20*).

In addition, the widespread low-wage job accessibility gains in bus connection areas might also ease the provision of sufficient quantities of transit-oriented affordable housing, again by expanding the supply of transit-oriented sites. In addition, this pattern calls into question claims that rail transit benefits only the lucky few who both live and work near it, while the weaker accessibility gains seen in bus connection areas for low- and medium-wage workers than for high-wage workers highlight the importance of planning feeder bus service specifically to enhance social equity.

TABLE 3 Model Predictions, Relative Accessibility Changes

Location Types	Low-Wage Jobs	Medium-Wage Jobs	High-Wage Jobs
Downtown LRT	30.17%	23.40%	18.14%
North LRT	39.56%	36.46%	39.30%
South LRT	188.96%	174.22%	240.00%
Suburb LRT	83.69%	89.14%	221.71%
Connection LRT	13.66%	15.07%	24.62%

COMMUTER FLOW ANALYSIS

The accessibility models described above help to quantify the number of jobs that could be reached by low-, medium-, and high-wage workers before and after light rail implementation. They describe what was possible at the starting point of the analysis and what became possible after the opening of the Twin Cities' first modern transitway. Possibilities, or impossibilities, however, do not necessarily equal realized gains or losses. To put it simply, the ability to commute to a given job by transit is not the same as being hired for that job and starting to make the commute. The following section quantifies the extent to which low-wage, high-wage, and all workers have changed their places of residence and to what extent low-paying, high-paying, and all employers have changed their places of business to take advantage of accessibility gains conferred by light rail and connecting bus service.

Approach

At their hearts, the models examining relocation behavior and displacement effects hinge on the counting of individual commutes. The home and work locations of these commutes are geocoded at the census block-group level. These counts stem from the LEHD home-to-work commute flow data [also referred as the origin–destination (O-D) matrix data] collected by the Census Bureau during the years 2002 and 2006. These data provide a matrix of block-to-block commute counts for low-wage, high-wage, and all workers. The analysis excludes commute records that either have an origin block centroid or destination block centroid more than a ¼ mi away from the nearest transit stop. The commute data were collected at the block level rather than the block-group level, but the Census Bureau deliberately reduces the precision of block-level demographic data to protect confidentiality for respondents. Aggregating block-level commute counts to the block groups containing their origins and destinations addresses this issue.

Three ordinary least squares regression models were used to estimate the 2002–2006 changes in the number of low-wage, high-wage, and all commuters making commutes that could reasonably be made using light rail (including direct bus connections) as a function of origin and destination location in station areas or bus connection areas, O-D distances to nearest transit stops, and surrounding social conditions. In interpreting the models' results, it is important to keep in mind that the dependent variables represent changes in numbers of commuters between the two observations rather than the actual commute flow counts.

Table 4 shows the results of the regression models. The adjusted R^2 values show high goodness of fit for all three models, particularly with low-income commuters as the dependent variable. This model has an adjusted R^2 of 0.338; in other words, it explains 33.8% of the 87 observed variability in commute flow changes. Especially considering that the dependent variable considers all commutes, regardless of mode choice, while the independent variables only consider transit service characteristics and (at least somewhat) transit-related demographics, this is impressive model performance. These good model fits suggest that transit service is important in determining commuting patterns within the transit service area. In addition, the better still model fit with low-income commuters considered in the dependent variable speaks to the special importance transit has in determining low-income commuting patterns.

Low-wage commute origins increase in a statistically significant manner in northern neighborhood station areas and bus connection areas, while low-wage commute destinations increase in downtown station areas, suburban stations areas, and bus connection areas. High-wage commutes, by comparison have more origins in downtown station areas, and more

TABLE 4 Commute Flow Regression Models

	Response: Change in		**Low-Wage**		**High-Wage**		**All**
	N = 395,920						
	Adj. R^2		0.338		0.114		0.171
	F		7,491.55		1,895.07		3,020.81
	Pre-LRT commutes	–	0.5814***	–	0.2653***	–	0.2802***
Destination	Stop distance	–	0.8207***	–	0.6226***	–	1.4773***
	Downtown LRT		0.5241***		1.5058***		1.8914***
	North neighborhood LRT	–	0.0891***	–	0.3336***	–	0.3640***
	South neighborhood LRT	–	0.0794***	–	0.6951***	–	0.5287***
	Suburb LRT		0.1354***	–	0.2684***	–	0.5036***
	Bus connection		0.0839***		0.0240***		0.0874***
	High-frequency bus		0.0718***	–	0.0280***		0.0637***
	Downtown non-LRT		0.0180***		0.0020***		0.0152***
Origin	Stop distance	–	0.7940***	–	0.8985***	–	1.7809***
	Downtown LRT		0.0265		0.3019***		0.2713***
	North neighborhood LRT		0.1156***	–	0.0459**		0.1283***
	South neighborhood LRT	–	0.0380**	–	0.0025	–	0.0614*
	Suburb LRT	–	0.0707	–	0.0873	–	0.1823
	Bus connection		0.0177***		0.0060		0.0170*
	High-frequency bus	–	0.0076*	–	0.0082	–	0.0287***
	Downtown non-LRT		0.0136***		0.0068***		0.0174***
Demographics	% Black		0.0906***	–	0.0661***	–	0.0026
	% Asian	–	0.0320	–	0.2702***	–	0.4554***
	% Hispanic	–	0.0915***	–	0.1424***	–	0.2852***
	% Single-parent families	–	0.0778***		0.0383	–	0.1061***
	% College degree	–	0.0509***		0.1073***		0.0813***
	% Owner-occupied housing	–	0.1139***	–	0.0476***	–	0.1883***
	% Carless households		0.0062	–	0.0750**	–	0.0561
	Median income ($1,000)		0.0002*		0.0008***		0.0007**
	Housing units/acre		0.0048***		0.0031***		0.0066***
	O-D distance (mi.)	–	0.0188***	–	0.0077***	–	0.0215***
	Constant		0.2190***		0.2325***		0.5200***

NOTE: *$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

destinations in downtown station areas and bus connection areas. (Note that though commute origin and destination conditions are described by separate sets of variables, the model's response variable is commute trips, not origin and/or destination points. The unit of this variable is commutes per block group-level O-D pair.)

Distance to nearest transit stop is consistently significant, and, as one would expect, negative. For low-wage and all commutes, stop distance is more strongly negative at the destination end of commutes, aligning with common expectations of reduced walking tolerances at the work end of transit commutes, as compared with the home end. High-wage commutes show the opposite pattern, though this may simply reflect high-wage workers lower reliance on transit, and, consequently, transit stop locations' lesser relevance to their commuting patterns.

The regression coefficients above are difficult to interpret directly, especially in light of the unit of the response variable. To ease interpretation of the overall trends found by the models,

Table 5 shows model predictions of the net changes in low-wage workers and jobs in station areas and bus connections.

Low-wage workers increase in all station areas, but most notably in northern neighborhood station areas. By contrast, low-wage jobs only increase in downtown and suburban station areas, by far to the greatest degree in downtown station areas. However, the greatest growth by far in both workers and jobs occurs in bus connection areas, despite a lower intensity in terms of commute O-Ds per block group pair.

Discussion of Commuter Flow Analysis

In interpreting these results, it is crucial to bear in mind that station and connection areas are defined based on a relatively restrictive ¼-mi (400-m) radius and that the data for the "after" observation date are from less than 2 years after light rail implementation. The model prediction may hint at the beginnings of a trend but likely understate the eventual result. Even so, the commuter flow models indicate that low-wage workers and jobs are increasingly locating in areas that allow them to take advantage of the job access and labor supply access benefits of light rail and associated bus service changes. The size of the growth in workers and jobs in areas served by bus routes offering direct light rail connections is striking and drives home the point that the much larger area covered by connecting bus routes allows bus connections to benefit many more workers than station areas themselves, despite lesser intensity of accessibility benefits.

CONCLUSIONS AND RECOMMENDATIONS

This research also shows that light rail can provide significant benefits to low-wage workers, serving as a counterforce to spatial mismatch problems by offering convenient, reliable, all-day access to both urban and suburban employment centers. The research also shows that low-wage workers (and their employers) are locating in practically significant numbers in areas that allow them to take advantage of light rail, at least when bus–rail connections are considered. However, the employment accessibility gains of light rail–bus connections, while significant across all wage categories, flow disproportionately to high-wage workers. This fact calls for action: In planning feeder bus service for light rail lines, transit providers should focus on home and workplace locations of the working poor and transportation-disadvantaged.

TABLE 5 Model Predictions, Net Change in Low-Wage Commute O-Ds

	Worker Move-Ins		Job Move-Ins	
Location	Total Workers	Average (per BG pair)	Total Workers	Average (per BG pair)
Downtown LRT	103	0.123	2,258	0.543
North LRT	593	0.202	–300	–0.070
South LRT	124	0.047	–134	–0.061
Suburban LRT	4	0.019	347	0.154
Bus connections	14,134	0.108	12,788	0.103

NOTE: BG = block pair.

Light rail transit frees city and regional planners to consider jobs–housing balance at a corridor level rather than merely at a neighborhood level (*15*). An effective network of bus connections broadens that freedom even beyond the light rail corridor itself. In planning new rail services, cities, regional planning bodies, and transit providers should take advantage of this freedom by permitting and promoting transit-oriented development along bus routes offering rail connections, in addition to within station areas themselves. In addition to promoting rail-connected bus transit-oriented development in general, it would seem crucial to promote the development of affordable housing along rail-connecting bus routes, given the greater number of affordable units possible (as compared with station areas), and the already observed increases in low-wage workers and jobs in bus connection areas.

The Metro Blue Line has been a major success story for transit in the Twin Cities region. Based on this research, this success is due in large part to its highly effective integration into the surrounding local bus system. A fine-grained network of local bus connections serves to dramatically extend the impacts of light rail, making the Metro Blue Line's impacts truly regional in scope, despite the limited number of points it serves directly. This result turns the tired rail versus bus debate on its head: In the case of Minneapolis, at least, the answer is rail and bus. The findings of this research carry with them a stern warning, however, a warning not to bow to constant pressure for cost savings by failing to provide adequate local bus connection to light rail lines: An LRT line that succeeds as an enhancement and complement to surround bus service may well fail if it is implemented at the expense of bus service. This research may not directly ease the admittedly challenging task of obtaining funds for sufficient feeder bus service, but it provides a compelling argument for the need to do so.

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Integration of METRO Blue and Green Lines with Buses

Restructuring Bus Service Around New High-Frequency LRT Lines

JOHN DILLERY
SCOTT THOMPSON
Metro Transit

The application of light rail transit in the Twin Cities has been implemented within a hybrid urban–suburban corridor on one hand and within an entirely urban corridor on the other.

In June 2004 Metro Transit (Transit) opened its first light rail line along Hiawatha Avenue, which included a major restructuring of bus service in the central south area of Minneapolis–Saint Paul and suburbs. The METRO Blue Line, a hybrid urban–suburban corridor, connects downtown Minneapolis with the Minneapolis–Saint Paul International Airport and the Mall of America.

In June 2014 Metro Transit opened the region's second light rail line. The METRO Green Line is an entirely urban line, operating mainly along University Avenue between downtown Saint Paul, the University of Minnesota, and downtown Minneapolis.

As part of the planning and implementation of these light rail lines, Metro Transit revised about half of its route network that serves over half of all of the bus riders.

This paper describes the opportunity that the METRO Blue Line along Hiawatha Avenue and the new METRO Green Line on University Avenue brings to improving transit in the Minneapolis–Saint Paul region. The service enhancement offered by these light rail lines is as much about high passenger carrying capacity as it is about frequency. With the METRO Blue Line, most of the riders come by walking, connecting bus service or park-and-ride. With the METRO Green Line, all riders come by walking or connecting bus service, not park-and-ride. The planning standards that went into making the bus and rail network effective were the same for both light rail lines. The planning priorities and outreach processes were different.

The planning process for the METRO Blue Line included traditional outreach techniques with stakeholders in the central south area of Minneapolis–Saint Paul and adjacent suburbs. A more extensive, and unconventional for Metro Transit, approach to outreach was followed for the METRO Green Line plan. Unlike the Blue Line, for which a concept bus plan was developed in advance of public review, with the Green Line, the stakeholder engagement process started a year prior to any route and schedule planning. This approach was a major help as Metro Transit staff redesigned the bus network for integration with the METRO Green Line as the bus plan changed very little from concept to final implementation. This indicates the extra engagement was worthwhile.

The METRO Blue Line bus plan relied on a Congestion Mitigation Air Quality (CMAQ) grant and some bus route savings to restructure and extend some bus lines to the new stations. With the Green Line bus plan, Transit was able to reinvest all of the resources from the east–west oriented bus service that was replaced by the new line. This reinvestment was focused on providing frequent connecting bus service traveling north–south, and in several cases, on nearby parallel east–west routes to the METRO Green Line.

The paper ends with an update about how the service is performing and lessons learned.

THE TWIN CITIES EXPERIENCE

The introduction of the two light rail transit lines, the METRO Blue Line and METRO Green Line, offered an extraordinary opportunity for redesigning the transit network. The METRO Blue Line opened in two phases, completed between downtown Minneapolis and the Mall of America in December 2004. The METRO Green Line opened completely between downtown Minneapolis and downtown Saint Paul in June 2014.

This paper will compare and contrast the ways in which bus service was redesigned around the METRO Blue and METRO Green lines and describe the results as of 2015.

Two Corridors: What Is the Same?

These two corridors are the source of the majority of rides taken on the Metro Transit system in the Twin Cities, with approximately 300,000 rides. The two plans improved on the already good crosstown bus network in both Minneapolis and Saint Paul. Both lines serve downtown Minneapolis, the most transit-oriented commercial node, with the highest travel market share for transit in Minnesota. The stations were placed so that direct access from the existing bus routes was easily accessible. Transit staff avoided creation of short linear bus routes or circulators in both plans.

The frequency of service for these two lines was kept at compatible levels, daily. The METRO lines operate every 10 min during the day, every 15 min during early morning and evening hours, and every 30 min during most very early and very late hours. Green Line trains run hourly between 1:00 and 4:00 a.m. Blue and Green trains alternate by uniform intervals on the common section along 5th Street in downtown Minneapolis.

The connecting bus lines are timed as much as possible with frequencies that fit well with the METRO Blue Line and Green Line frequencies.

Two Corridors: What Is Different?

The METRO Blue Line serves a hybrid urban–suburban area, while the METRO Green Line serves an entirely urban area. The Blue Line relies heavily on park-and-rides located in the suburban south end, whereas the urban Green Line has no park-and-rides.

The Blue Line serves one of the largest shopping malls in the USA: The Mall of America. The Blue Line also serves the Minneapolis–Saint Paul International Airport, one of the largest employers in the region. Unique in suburbs, parking is not free at the airport. Trains run 24 h per day between the airport terminals and 21 h per day elsewhere. The three overnight hours' service is paid for by the Metropolitan Airports Commission. No fare is charged for any trips taken between the two airport terminals. In exchange, the Metropolitan Airports Commission supports the maintenance of the two airport stations. The Terminal 1–Lindbergh is the only subway station on either METRO line.

The Green Line serves the two downtowns and the University of Minnesota, one of the largest commuter campuses in the United States. Trains run 24 h per day. Actively enrolled University of Minnesota students and employees holding a campus zone pass can ride between three stations on campus: West Bank, East Bank, and Stadium Village. This campus zone pass program is funded by the University of Minnesota.

WHAT IS UNIQUE ABOUT THE METRO BLUE LINE PLAN?

METRO Blue Line Plan Development and Stakeholder Process

Demographics and Pre–Blue Line Service, 2003

Starting in 1999 Metro Transit began a series of nine subregional studies of its bus transit services around the Twin Cities region. These studies have lead to significant restructuring of bus routes. In 2003, the Sector 5 plan recommended restructuring transit service in south Minneapolis, Bloomington, Edina, Richfield, and in an area of Saint Paul south of I-94 and west of downtown. Implementation occurred in three phases starting in June 2004 and was completed in December 2004. Sector 5, (or Central-South), includes several major transportation corridors: Hiawatha Avenue, I-35W South, and I-494. The METRO Blue Line (Hiawatha) plan is a part of the larger Sector 5 plan.

Out of the 55 routes operating in Sector 5, 27 now connect directly to the Blue Line outside of downtown Minneapolis. In 2003, Sector 5 transit accounted for more than 50% of Metro Transit rides (36.4 million) and just 40% of Metro Transit service hours. Some 500,000 residents and 500,000 jobs are located in this sector. The Sector 5 Existing Conditions Report depicts transit successfully serving a densely developed urban area, and outlines opportunities for transit in suburban corridors that have developed strong employment and residential concentrations.[1]

The pre–Blue Line service is characterized by

- Good coverage,
- Complexity of some routes,
- Park-and-ride lots too small to grow ridership and improve efficiency,
- Bus stop spacing too close on many routes, slowing bus operations, and
- Opportunities to improve frequency and span of service in strong markets.

Public Involvement

As part of evaluating existing service and gathering community input, Metro Transit convened stakeholders, from transit customers and community groups to elected officials, in several meetings throughout the study area. The purpose of the community outreach in early 2002 was to ask stakeholders to prioritize the value of competing transit service objectives, mainly coverage versus frequency. Feedback suggested that the productivity and efficiency of transit service in Sector 5 were highly valued. This guided the development of the concept plan, a process continued in early 2003 with six public meetings and a public hearing to receive comments on the concept plan. This followed our traditional public outreach process.

The major themes voiced by stakeholders to improve the productivity of service included

- Faster service in major corridors such as Hiawatha Avenue, Lake Street, I-35W, West 7th Street;
- Faster service between Minneapolis and Minneapolis–Saint Paul International Airport for workers and travelers;
- Improved frequency and span of service, especially on weekends;

- Improved/added crosstown bus service in cities between neighborhoods and suburbs;
- Simpler route structures, fewer route branches;
- Expanded park and rides to better meet projected demand;
- Increased distance between bus stops to not exceed eight per mile on local routes;
- Added service in the I-494 market between Richfield and Bloomington, via crosstown and reverse-commute transit; and
- Reinvest transit resources to better fit local development and transit markets.

Key Plan Objectives and Strategies

Evaluation of existing conditions in the Hiawatha Avenue Study Area and consideration of the most common topics from the public input process suggested seven primary opportunities to improve the productivity and effectiveness of transit service within the study area (Figure 1):

- Strengthen the bus route network grid to enhance neighborhood to neighborhood travel;
- Connect bus routes with trains at key Blue Line stations;
- Improve service frequency in exchange for longer walk distances;
- More riders at fewer stops supports better waiting facilities since most people will walk to more frequent service;
- Enhance off-peak service because increasingly, people need to travel outside the traditional rush-hour commute periods;
- Improve bus-to-bus connectivity; and
- Improve bus service to major destinations as identified by public input.

These basic observations led to the following service design principles in the concept and recommended plan:

- Provide convenient and reliable bus and train connections at key Blue Line stations;
- Generally improve the frequency of connecting bus service to every 20 min seven days a week, which is compatible with the Blue Line's 10-min frequency;
- Expand the hours of service for most bus routes that connect with the Blue Line seven days a week;
- Reduce transit service redundancy between bus and LRT in the corridor and shift resources from reduced bus service on Hiawatha Avenue and I-35W to improve connecting bus service;
- Provide faster, more direct service to major destinations in the area;
- Fill in the east–west crosstown bus route network; and
- Optimize route length to maximize effectiveness, efficiency, and productivity.

Transit Service Changes

The primary emphasis of the plan was to reduce service on radial bus routes replaced by Blue Line trains and to shift those resources into improved coverage, frequency, and hours of service

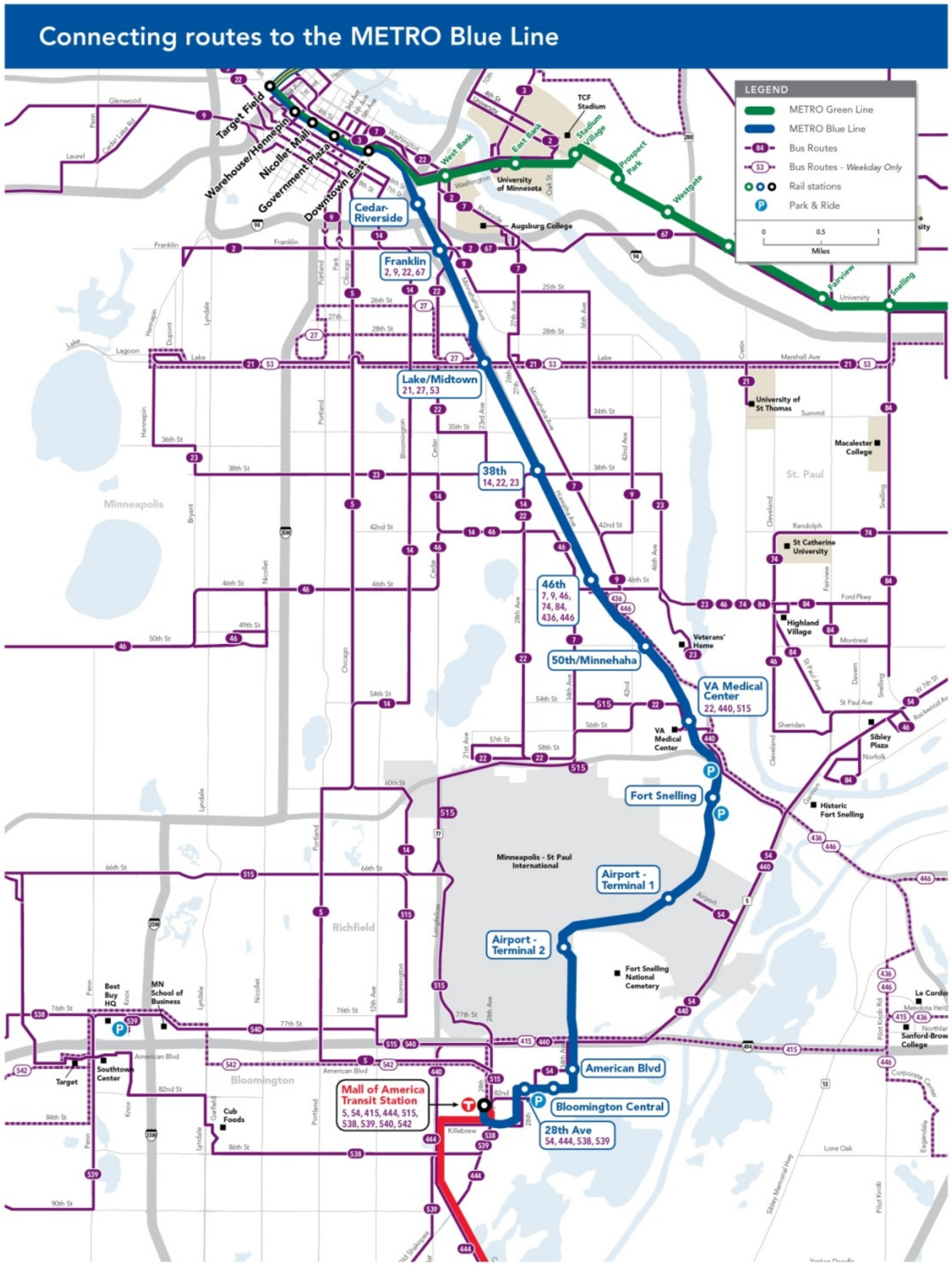


FIGURE 1 METRO Blue Line corridor map.

on the connecting bus routes. Today, there are 29 bus lines connecting with the Blue Line at stations outside of downtown Minneapolis. Improved frequency of service on selected bus routes improved the reliability of and connections between routes. Bus frequencies were scheduled compatible with those of the Blue Line to provide reliable and consistent connections (Table 1).

The bus service connecting with the Blue Line was changed to positively address many of the themes listed above. These themes became the objectives of the Sector 5/Blue Line plan.[2]

The METRO Blue Line plan includes some good examples of positive service changes that address these themes.

Hiawatha Avenue Corridor (Parallel Routes 7, 9, 14, 22) Route 7 was replaced by the METRO Blue Line in the suburban segment. Trains replaced buses between the airport and Minneapolis, cutting one-way travel times nearly in half, to 26 min. Route 7 now serves only the City of Minneapolis and is the closest parallel route to Hiawatha Avenue, Minnehaha Avenue being about ¼ mile to the east. Connections with the Blue Line are at 46th Street Station, provides access to the Mall of America in Bloomington, formerly on Route 7.

Stakeholders' themes addressed: Much faster and more frequent service Minneapolis–airport, simpler routes with no branches.

Route 9 (former 20), was rerouted from Saint Paul–Highland Park to the 46th Street Station to connect the neighborhoods along the west bank of the Mississippi to the Blue Line. Route 9 was restructured to serve Franklin, Park, Portland avenues south of downtown Minneapolis. Stakeholders' themes addressed: Simpler route, easier crosstown connections.

Route 14 features a new branch from Bloomington Avenue via 42nd Street and 28th Avenue to the 38th Street Station. Stakeholders' themes addressed: easier crosstown connections albeit with a slightly more complicated route structure.

Route 22 (former 19), was extended to VA Medical Center and rerouted into the 38th Street Station. The route now serves only the City of Minneapolis. The connections with the Blue Line are set at 38th Street and at VA Medical Center stations, provide access to the Mall of America in Bloomington, formerly on Route 19. Stakeholders' themes addressed: simpler route, easier crosstown connections.

East–West Crosstown Connections (Routes 2, 9, 21, 23, 27, 46, 53, 67, 74, 84, 515) Routes 2, 9, 67 (former 8) connect with the Blue Line at Franklin Avenue Station. Stakeholders' themes addressed: easier crosstown connections and much better frequencies and service span.

Routes 21, 27, 53 connect with the Blue Line at Lake Street–Midtown Station. Stakeholders' themes addressed: easier crosstown connections.

Route 23 connects with the Blue Line the 38th Street Station in an off-street bus loop. Stakeholders' themes addressed: easier crosstown connections and slightly better frequencies and service span.

Routes 46, 74, 84 connect with the Blue Line at the 46th Street Station in an off-street bus loop. Route 46 was extended to Highland Park in Saint Paul. Routes 74 and 84 were extended from Highland Park to the 46th Street Station. Stakeholders' themes addressed: easier crosstown connections, strengthen the bus network grid.

Route 515 connects with the Blue Line at VA Medical Center and at Mall of America stations. Average station spacing outside of downtown is close to one mile, so the bus connections provided were considered essential to serve the riders more than ½ mi from stations. Stakeholders' themes addressed: easier crosstown connections.

Most routes operate very efficiently on 60-, 90-, or 120-min schedule cycles, with most layovers just adequate for reliable service. The service plan maximized hours given to providing revenue transit service. Efficient schedule cycles are especially critical during the lower frequency periods. Stakeholders' theme addressed: Optimize effectiveness and efficiency to improve transit system's productivity.

TABLE 1 Before-and-After Frequency Comparison for METRO Blue Line

	Weekday Off-peak		Weekday Peak		Saturday		Sunday	
Before and After Routes	2003	2015	2003	2015	2003	2015	2003	2015
METRO Blue Line	0	**10**	0	**10**	0	**10**	0	**10**
2 – Franklin Ave / Riverside Ave /U of M / 4th/ 8th St SE	20	**15**	20	**10-15**	30	**20-30**	30	**20-30**
5 - Chicago Ave / Portland Ave / Mall of America (MOA)	7.5	**7.5**	5	**5**	10	**10**	10-15	**10-15**
7- U of M / Riverside Ave /27th /Minnehaha Ave	20	**30**	15	**15-30**	30	**30**	30-60	**30-60**
9 (former 20) - Portland / Park**/** Franklin Ave./25th St / 36th / 46th	30	**30**	30	**20-30**	30	**30**	60	**30**
14 - Bloomington Ave / 42nd St / 38th St	20	**20**	12	**12**	20	**20**	30	**20**
21 – Selby Ave / Lake St / Uptown	7.5	**6-12**	6	**6-15**	7.5	**6-15**	10	**8-15**
22 (former 19)– Cedar Ave / 38th St / 28th Ave/ VA Medical Ctr.	20	**20**	12	**10-20**	20	**20**	30	**30**
23 – Bryant / 38th St. / 46th Ave. / Vets Home	30	**20**	30	**20**	20-30	**20**	30	**30**
46 – St Paul Ave / 46th St Station / 42nd St / 50th St. / Edina		**30**		**30**		**30**		**30-60**
53 (former 191) – Uptown**/** Lake St / DT St Paul			20-30	**15**				
54 – St. Paul / W 7th St / Airport / Mall of America	30	**15**	30	**12-15**	30	**15**	30	**20**
67 (former 8) Mpls / Franklin Ave / University Ave / Minnehaha	30	**20**	20	**20**	30	**20**	30	**30**
69 – W 7th St. / Fort Snelling / Highland Park	15	**See 46,54**	10 to 30	**See 46,54**	30 to 60	**See 46,54**	30 to 60	**See 46,54**
74 (former 64) – 46th St Station/ Randolph Ave	15	**20**	15	**15**	20	**20**	30	**30**
84 – Roseville / Snelling Ave / 46th St / W7th St – Davern St	15	**10**	15	**10**	15	**10**	15	**10-15**
134 – Mpls. I-94 / Cretin / Cleveland Ave			10	**10-20**				
180 – Minneapolis / Mall of America (MOA) Express	20		15-20		20-30		20-30	
415- MOA / Eagan Employers			30	**30**				
436 – 46th St Station / Eagan Employers				**60**				
440 – MOA / Eagan / Apple Valley Transit Station	60	**See Red Line**	60	**See Red Line**	60	**See Red Line**	60	**See Red Line**
442 – MOA / Apple Valley / Burnsville Transit Station	60	**See Red Line**	30	**See Red Line**		**See Red Line**		**See Red Line**
444 – MOA / Eagan / Burnsville / Savage	30	**30**	30	**30**	60	**60**	60	**60**
445 – MOA / Cedar Grove Transit Station / Eagan	60	**See Red Line**	30	**See Red Line**	60	**See Red Line**	60	**See Red Line**
446 - 46th St Station / Eagan Employers		**60**		**30-60**				
449 – Downtown Mpls./ MOA / Eagan Employers			30	**See 446**				
515 (former 15) – Southdale / 66th St. / MOA / VA Med Ctr	20	**15**	10 to 20	**10 to 15**	30	**15**	30	**20**
530 - Airport Inter-Terminal Shuttle	10		10		10		10	
538 – Southdale / York Ave / 86th St / MOA	30-60	**30-60**	30-60	**30**	30-60	**30-60**	30-60	**30-60**
539 – MOA /Old Shakopee/Normandale College / Best Buy, Inc	60	**30**	30	**30**	60	**60**	60	**60**
540 – MOA / W. 76th / E 77th St. / Cahill	30-60	**30-60**	30	**15**	0	**60**	0	**60**
542 - MOA / E. 79th / W. 84th St. / Norman Ctr.		**60-120**		**30**				
903 - **METRO RED Line –** MOA /Cedar Ave./ Apple Valley BRT	0	**15**	0	**15**	0	**30**	0	**30**

Transit Service Update

While Metro Transit's operating budget was reduced in 2003, the plan met the objectives within the amended annual operating budget because of the addition of a federal CMAQ grant of $14 million, which allowed about a 7% increase in service for approximately three years. Unfortunately, Metro Transit's operating budget was reduced again in 2005, which resulted in off-peak service reductions on some connecting bus routes to every 30 min.

Public response to the new service continued after 2004. Pre-Blue Line, Route 7, the radial route connecting downtown Minneapolis, Minnehaha Avenue, Minnehaha Park, Fort Snelling, the Minneapolis–Saint Paul International Airport, and the Mall of America, was shortened to the Lake Street-Midtown Station. The new Route 27 crosstown replaced Route 7 on Minnehaha Avenue and ended north of the airport on 34th Avenue at Hwy. 62. In response to customer requests, Route 7 was restored between downtown Minneapolis and Minnehaha–34th Avenue in 2008.

Facility Improvements

- Off-street bus loops were included for cross-platform transfers at the following stations: 38th Street, 46th Street, and Mall of America. The off-street bus loops function as terminals for18 bus lines and allow optimal levels of connecting bus service to be provided efficiently (see Figure 2 for example of an off-street bus loop).
- Installation of the loops at 38th and 46th streets was made easier because of available right-of-way along State Highway 55 (Hiawatha Avenue).
- Large park-and-rides were constructed as part of the Hiawatha (METRO Blue Line) Project. Previously no park-and-rides existed in the southern end of the corridor. Today, there are 2,456 park-and-ride spaces available on the Blue Line. On average, usage is about 50%. Travel sheds extend farther than typical, 10 mi or more.
  - Fort Snelling Station includes two surface lots with a capacity of 1,073 spaces. Current average use is 707 or 66%. Usage can be much closer to capacity for events.
  - 28th Avenue Station in Bloomington has a parking ramp and small surface lot with a total of 1,383 spaces. Current average use is 512 or 37%. Events often increase usage.

Plan Impacts

Metro Transit staff worked extensively to refine the plan to minimize negative impacts on transit customers, and there were few segments of routes where service was eliminated or reduced. In all cases, alternate transit service was within a 1/4 mi of residents and businesses along these routes.

Park and riding in unauthorized locations or "hide and riding" does occur near the 50th Street/Minnehaha Park, 46th Street, 38th Street, Lake Street, and Franklin Avenue stations. Perhaps as many as 300 cars are seen parked for long periods near these stations. The City of Minneapolis offers a neighborhood residential permit parking program, and this has been adopted on some blocks adjacent to these stations to protect neighborhoods from hide and riding.

Bus stop spacing has not changed significantly overall since the plan was implemented, however, Metro Transit staff will be pursuing options to optimize local bus stop spacing.

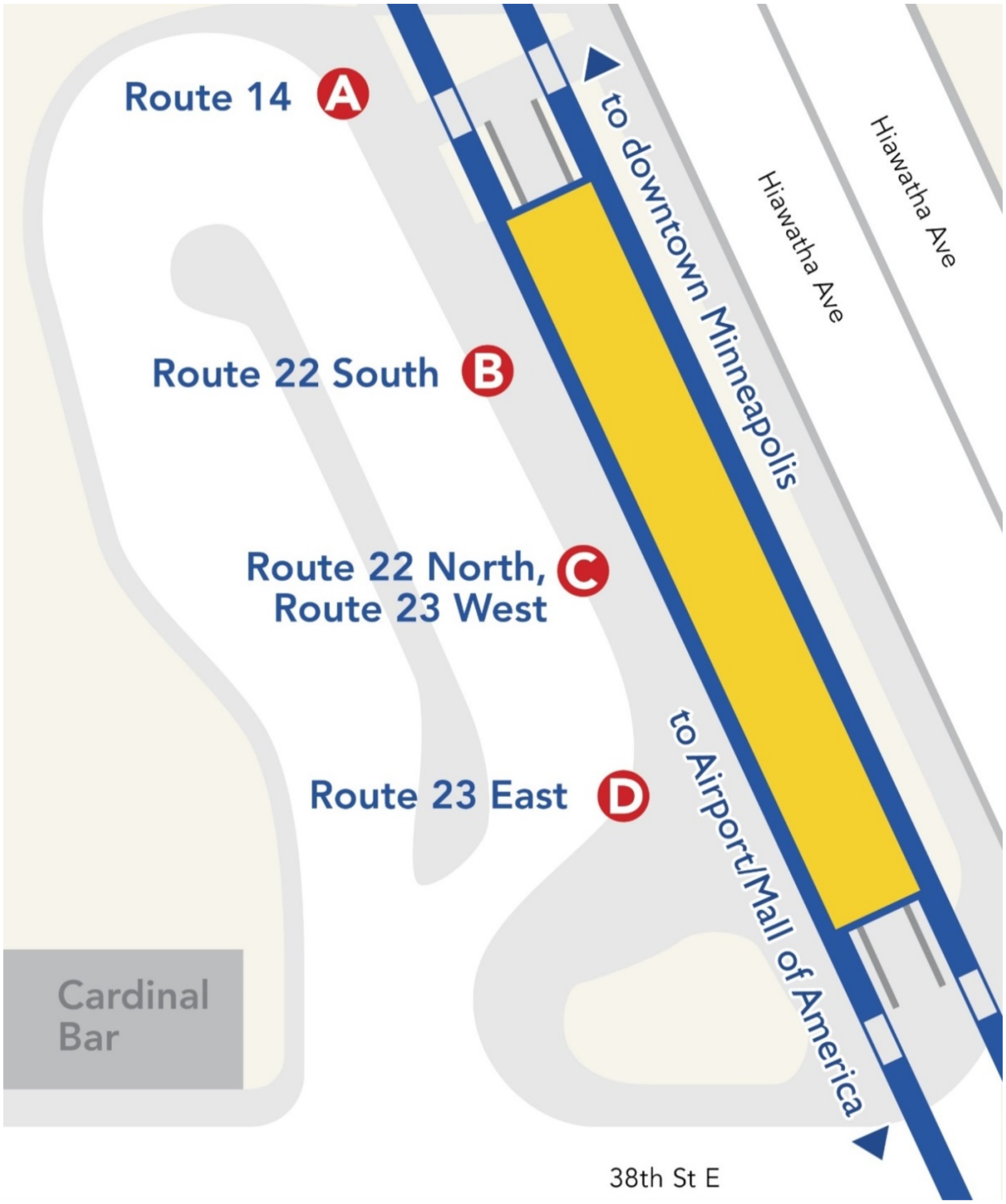


FIGURE 2 METRO Blue Line 38th Street station map.

Traffic flow around the Blue Line was an issue in the first years of operation. Traffic on State Highway 55–Hiawatha Avenue and at the major cross streets was slowed noticeably and traffic counts actually declined slightly on Hiawatha Avenue. Public reaction was strong and negative. Diligent efforts by the City of Minneapolis, Hennepin County, and the Minnesota Department of Transportation to adjust and refine traffic signal systems have resulted in improved traffic flow and generally shorter queues at signals, including the heaviest crossings at 38th and 46th streets. The Blue Line has been almost entirely insulated from traffic congestion on parallel Hiawatha Avenue thanks to grade separation at Franklin Avenue, Lake Street, and State Highway 62, and the application of signal preemption at the many street crossings along the line.

The METRO Blue Line was projected in 2003 to provide an estimated 9.5 million annual rides by year 2020. This goal has been surpassed. Projected annual rides for the METRO Blue Line for year 2015 are about 10.4 million, a true measure of success. Bus ridership is lower on weekdays, as expected due to shifts to the METRO service, yet higher on weekends indicating a much greater off-peak ridership after 12 years of rail service. Overall, there are now about 27,000, or 29%, new rides per day thanks to the METRO Blue Line and connecting buses.

WHAT IS UNIQUE ABOUT THE METRO GREEN LINE PLAN?

METRO Green Line Plan Development and Stakeholder Process

Demographics and Pre–Green Line Service, 2013

The METRO Green Line (Central Corridor) Transit Service Area is bounded by the Mississippi River on the south, I-35E on the east, Larpenteur/East Hennepin avenues on the north, and by Hiawatha Avenue, East Lake Street, and the Mississippi River on the west. The study area is almost completely urban, including downtown Minneapolis, downtown Street Paul, and the University of Minnesota, and covering many neighborhoods of Street Paul, Minneapolis, and the suburbs of Lauderdale, Falcon Heights, and Roseville. The population of the study area is about 246,000, and as of 2008, there were about 357,600 jobs in the study area. This represents about 8.6% of the population and 22% of the employment in the entire metropolitan area.

In contrast to the Blue Line corridor, this area is particularly known for its concentration of postsecondary educational campuses and the concentrations of student populations. There are about 91,000 students at the colleges and universities in the study area. Significant educational institutions include the University of Minnesota (Minneapolis and Street Paul campuses), Augsburg College, Concordia University, Hamline University, Macalester College, Street Paul College, Street Catherine's University, the University of Street Thomas, and William Mitchell College of Law.

The Central Corridor Transit Service Study Existing Conditions Report documents ridership collected at every bus stop in the sector.[3] It depicts a transit system successfully serving the densely developed core urban area. It outlines opportunities for transit in the urban center of the Twin Cities that has strong employment and residential concentrations.

The pre-METRO Green Line service is characterized by

- Good overall existing route network design and coverage,
- Some gaps in the crosstown grid network,
- Good ridership during all times of the day and day of week, and
- A lack of adequate frequency and span of service on some routes.

Public Involvement

Metro Transit staff worked with stakeholders, including transit customers and community/neighborhood groups, much more extensively than was done for the Blue Line. For the Blue Line plan, staff developed a concept plan and presented it to the stakeholders for their review and comment. With the Green Line (Central Corridor) public involvement process, staff simply asked stakeholders to identify their major travel patterns and service improvement themes. Taking this input, transit service performance, and travel behavior data into account, the concept plan was then developed.

The four primary methods used to gather public input for the pre-Concept Plan were

1. A series of meetings with neighborhoods and community groups, residents, and businesses;
2. Three public open houses;
3. A public input form on the Metro Transit website; and
4. Trusted Advocates contracted by the District Councils Collaborative of Saint Paul and Minneapolis (DCC).[4]

Major travel patterns and service improvement themes voiced by stakeholders included

- Frequency improvements on Raymond Avenue and Dale Street;
- Easier neighborhood-to-neighborhood travel without having to transfer in downtown;
- Better timed connections in general; and
- New crosstown routes, such as on Lexington Parkway in Street Paul.

Staff used the feedback received during the pre-Concept Plan outreach to develop a concept service plan, which became the topic of a formal public review period. As in the previous phase, Metro Transit used several different outreach strategies to reach different stakeholders to ensure broad public engagement. The five primary ways used to communicate the concept plan and gather public input were

1. Contact neighborhoods and community groups, residents, and businesses;
2. Notices to current customers and general public;
3. Five public meetings;
4. A variety of public input methods, such as comment cards and e-mail; and
5. Trusted Advocates.

Metro Transit received more than 800 comments from 650 contacts. Feedback from stakeholders and public comments identified areas in the plan that warranted modification. The greatest number of comments was about proposed Route 83–Lexington Parkway. The segments north of Como Avenue and south of Randolph Avenue were redesigned as a result.

Route 94 was the route that received the second highest number of comments (85). The primary concerns with this route were the loss of midday service, a longer commute time, and loss of stops at Marion Street near Ravoux Hi-Rise and at Snelling Avenue. Midday service was retained. Route 16 was rerouted via Marion St to replace the access lost from removing Route 94.

The Concept Plan was modified to address many of the concerns highlighted by public comments, while staying within the project operating budget. Specifically, five routes were altered in response to public comment. An open house was held on October 10, 2012, to share Concept Plan modifications with the community.

Key Plan Objectives and Strategies

Evaluation of existing conditions in the area and consideration of the most common topics from the public input process suggest six primary opportunities to improve the productivity and effectiveness of transit service:

- Strengthen the bus route network grid to enhance neighborhood to neighborhood travel;
- Connect bus routes with trains at key Green Line stations;
- Improve service frequency, because given a choice, most people will choose more frequent service within reasonable walk distances;
- Enhance off-peak service, because increasingly, people need to travel outside the traditional rush-hour commute periods;
- Improve bus-to-bus connectivity and connections to other study area bus routes; and
- Improve bus service to major destinations as identified by public input.

These basic observations led to the following service design principles in the concept and recommended plan:

- Provide convenient and reliable bus and train connections at key Green Line stations;
- Generally improve the frequency of connecting bus service to every 20 min seven days a week, which is compatible with the Green Line's 10-min frequency;
- Expand the hours of service for all bus routes that connect with the Green Line daily;
- Reduce transit service redundancy between bus and LRT in the corridor and shift resources from reduced bus service on University Avenue and I-94 to improve connecting bus service;
- Improve the transit connectivity among the many colleges and universities in the area;
- Provide faster, more direct service to major destinations in the area;
- Fill in the north–south crosstown bus route network; and
- Optimize route length to maximize effectiveness, efficiency and productivity.

Transit Service Changes

The primary emphasis of the plan reduced service on bus routes whose service was replaced by Green Line trains. Resources were shifted to improved coverage, frequency, and hours of service on connecting bus routes. Fourteen bus lines, including the new routes 30 and 83, now make connections with the METRO Green Line between the two downtowns (Figure 3). Bus service frequencies, made compatible with those of the Green Line, now provide reliable and consistent connections (Table 2). The major travel needs and service improvement themes voiced by stakeholders became the objectives of the Green Line (Central Corridor) plan.[5] The METRO Green Line plan includes excellent examples of positive changes.

East–West Parallel Connections (Routes 8, 16, 21, 63, 67) East–west routes that parallel the University Avenue corridor were adjusted to improve connections with the Green Line. Just one parallel radial route (63) in Street Paul was extended to connect directly with the Green Line at the Raymond Avenue Station.

Route 16 continues to provide local connections along University Avenue and with the METRO Green Line from downtown Street Paul to the neighborhood to the east of the University of Minnesota, modified via a new route on Marion Street west of the state capitol. Stakeholder feedback from the Ravoux Hi-Rise, located on Marion Street, and Metro Transit's decision to retain local bus service through this neighborhood was a result of the Trusted Advocate program. Residents of this neighborhood are not inclined to attend public open houses and public hearings. In fact, feedback about the proposed elimination of local bus service was not received until very late in the outreach effort and would not have been a known issue under our previous public input process.

Route 21 Selby Avenue–Lake Street continues to provide connections to University Avenue and the Green Line from Selby Avenue to the east and Marshall Avenue/Lake Street to the west. Stakeholders' themes addressed: improved frequencies.

Route 63 Grand Avenue was extended from the University of Street Thomas to Westgate Station via Cretin Avenue. Stakeholders' themes addressed: improved daily frequencies, span of service, easier crosstown connections, strengthen bus route network in Minneapolis and Saint Paul.

Route 67 Minnehaha Avenue was restructured to serve Franklin Avenue between Hiawatha Avenue (Blue Line) and University Avenue, replacing Route 8. It was extended on University between Raymond Avenue Station and Fairview Avenue Station, continued to cover Fairview and Minnehaha avenues to downtown Street Paul, ending there. Former Route 67 Smith Avenue /West Saint Paul service south of downtown Street Paul became part of Route 62 Rice Street. Stakeholders' themes addressed: improved frequencies and span of service daily.

North–South Crosstown Connections (Routes 30, 62/262, 65, 83, 84, 87) The north–south routes that had always crossed University Avenue at Dale Street (65), Snelling Avenue (21, 84) and Raymond Avenue (87) were improved to make frequent connections with the METRO Green Line, and a route (83) on Lexington Parkway was reintroduced. A new crosstown route (30) was created to northeast and north Minneapolis.

Route 30 Broadway Avenue crosstown was created for a new direct link between the METRO Green Line at Westgate Station and north and northeast Minneapolis. Weekday only service is provided initially, funded with a Jobs Access/Reverse-Commute (JARC) grant. Stakeholders' themes addressed: improved frequencies and span of service, strengthen the bus route network.

Routes 62/262 continue to provide direct service from the Rice Street Corridor to downtown Saint Paul. Route 62 now provides service to Smith Avenue / West Saint Paul. It also has an important crosstown function for travel to and from University Avenue and Minneapolis. Stakeholders' themes addressed: improved frequencies and span of service, strengthen the bus route network.

Route 65 no longer directly serves downtown Saint Paul via Selby on weekdays. Instead, all trips continue direct to Grand Avenue and connections with Route 63. Service was enhanced to more effectively connect with other lines, including the METRO Green Line, seven days a week. Route is a secondary crosstown, serving Rosedale Mall, and a neighborhood shopping center at University Avenue. Stakeholders' themes addressed: improved frequencies and span of service, strengthen the bus route network.

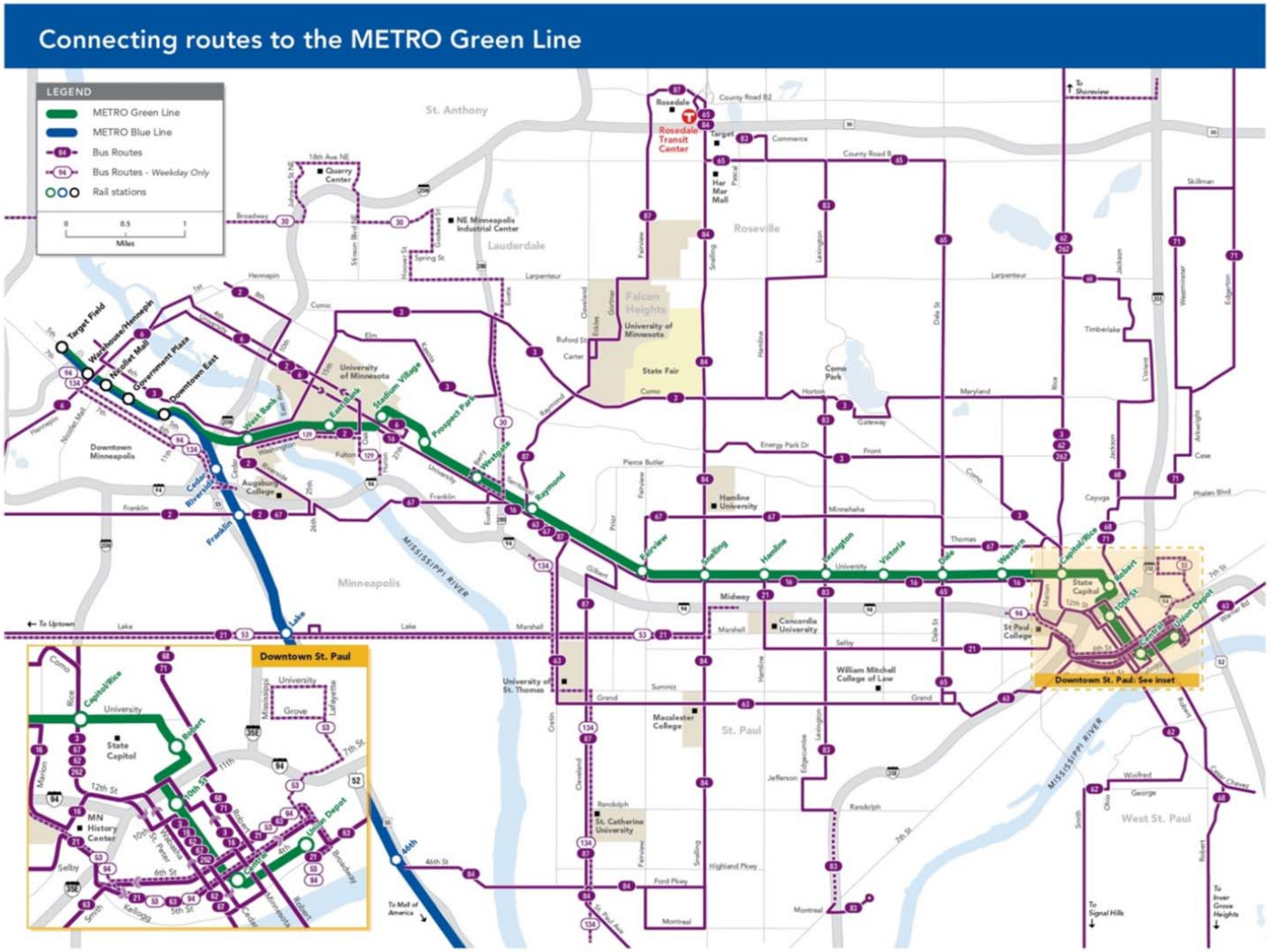


FIGURE 3 METRO Green Line corridor map.

TABLE 2 Before-and-After Frequency Comparison for METRO Green Line

Existing and Proposed Routes	Weekday Off-peak 2013	Weekday Off-peak 2015	Weekday Peak 2013	Weekday Peak 2015	Saturday 2013	Saturday 2015	Sunday 2013	Sunday 2015
METRO Green Line -Mpls/U of M/University Av/St. Paul *LRT*	0	**10**	0	**10**	0	**10**	0	**10**
2 - Franklin/Riverside/U of M/4th/8th St	5 to 15	**5 to 15**	5 to 15	**5 to 15**	20 to 30	**20**	20 to 30	**20**
3 - Mpls/U of M/Como/Front/Maryland/St. Paul	10 to 15	**10 to 15**	5 to 15	**5 to 15**	30	**30**	30	**30**
6 - Mpls/U of M/4th St/Univ. Av/Stadium Village	30	**30**	20	**20**	30	**30**	30	**30**
8 - Mpls/Franklin Av/Univ. Av (See Route 67)	30 to 40	**0**	30	**0**	0	**0**	0	**0**
16 - Mpls/U of M/University Av/St. Paul	10	**20**	8 to 12	**20**	10 to 15	**20**	15 to 30	**20**
21 -Marshall Av/Selby Av/St. Paul end only	20 to 30	**20**	15	**15**	20	**20**	20	**20**
50 - Mpls/U of M/University Av/St. Paul (See Green Line)	0	**0**	6 to 12	**0**	0	**0**	0	**0**
53 - Mpls/Lake St/Marshall Av/I-94/St. Paul	0	**0**	20 to 30	**20 to 30**	0	**0**	0	**0**
62 - Shoreview/Rice St /St. Paul	30	**30**	30	**30**	30	**30**	60	**30**
62 - St. Paul/ Smith Av/Signal Hills/W. St Paul	0	**30**	0	**30**	0	**60**	0	**60**
63 - Maplewood/E. 3rd St /St. Paul/Grand Av	20 to 30	**20**	13 to 30	**10 to 20**	30	**20**	60	**20**
63 – Raymond Av/University/Cretin Av	0	**20**	0	**20**	0	**20**	0	**20**
65 - Roseville/Dale St /St. Paul	30	**20**	30	**20**	75	**20**	75	**30**
67 – Smith /Signal Hills/W. St Paul (See Rt 62)	30	**0**	30	**0**	60	**0**	60	**0**
67 – Fairview/Minnehaha/Thomas Av**/**St Paul	30	**20**	20 to 30	**20**	60	**20**	60	**20**
67 – Mpls/Franklin Av/University Av**/**St Paul	0	**20**	0	**20**	0	**20**	0	**60**
68 – St. Paul/Robert St//Jackson St	30	**30**	10 to 30	**10 to 30**	30 to 60	**30 to 60**	30 to 60	**30 to 60**
71 – St. Paul/Arkwright St/Concord St	15 to 30	**15 to 30**	15 to 30	**15 to 30**	30 to 60	**30 to 60**	60	**60**
83 – Como Av/Energy Park/Lexington/W 7th St	0	**30**	0	**30**	0	**30**	0	**30**
84 - Roseville/Snelling Av/St. Paul/46th St/Mpls	15	**10**	15	**10**	15 to 30	**10**	30 to 60	**10**
87 - Roseville/Raymond Av/Cleveland/St Paul	30	**20**	30	**20**	0	**20**	0	**30**
94 - Mpls/ I-94 Express/St. Paul (See Green Line)	15	**30**	5 to 10	**5-10**	30	**0**	30	**0**
134 - St. Paul/Cleveland/Cretin Av/I-94/Mpls	0	**0**	10 to 20	**10 to 20**	0	**0**	0	**0**
144 - St. Paul /Snelling Av/I-94/ U of M/Mpls (See Green Line)	0	**0**	15 to 30	**0**	0	**0**	0	**0**
Routes via Huron Blvd Station:								
Local U of M Connection – Huron Blvd/Washington Ave	0	**0**	10	**10**	0	**0**	0	**0**
353 – Woodbury/St Paul/ I-94 Express /Mpls	0	**0**	1 trip	**1 trip**	0	**0**	0	**0**
355 – Woodbury/ I-94 Express**/** Mpls	0	**0**	10 to 15	**10 to 15**	0	**0**	0	**0**
365 – Cottage Grove/ I-94 Express**/** Mpls	0	**0**	15 to 30	**15 to 30**	0	**0**	0	**0**
375 – Oakdale/ I-94 Express**/** Mpls	0	**0**	10 to 20	**10 to 20**	0	**0**	0	**0**
452 – Mendota/ I-94 Express**/** Mpls	0	**0**	30	**30**	0	**0**	0	**0**

Route 83 was reinstituted on Lexington Parkway between 7th Street and the Roseville Super Target via Como Park. Stakeholders' themes addressed: This new crosstown minibus line enhances the grid network, filling a 2-mi gap between Snelling Avenue and Dale Street.

Route 84 Snelling Avenue was enhanced to match the frequency of the METRO Green Line during most hours. It is the primary crosstown in the corridor, serving Rosedale Mall, large neighborhood shopping centers, and two major colleges. Stakeholders' themes addressed: improved frequencies and span of service, strengthen the bus route network.

Route 87 Raymond and Cleveland avenues was enhanced to more effectively connect with other lines, including the METRO Green Line, seven days a week. It is a secondary crosstown, serving Rosedale Mall, a large shopping center at Ford Parkway, and three major colleges. Stakeholders' themes addressed: improved frequencies and span of service, strengthen the bus route network.

Facility Improvements

Unlike many Blue Line stations, the Green Line stations were not designed with off-street bus loops. Connecting buses, most of which operate through, cross University Avenue and extend long distances beyond it. Unlike with the Blue Line, ridership is equivalent both north and south of University Avenue, so service levels are the same and there is little need for bus turnarounds at University Avenue. The few bus lines ending at University Avenue near the Prospect Park Station on 27th Avenue SE and at the Westgate Station on Berry Street utilize on-street layovers.

Hide and riding has not been detected to a significant extent along the Green Line.

Plan Impacts

Metro Transit staff worked extensively to refine the plan to minimize negative impacts on transit customers. The plan implemented in June of 2014 reinforces the simplified route structure implemented in earlier sector plans, adds frequency, span of service and new crosstown service to meet the guidelines found in the Metropolitan Council's Transportation Policy Plan via a reinvestment of resources. Unlike the Blue Line plan, the Green Line replaced most of the parallel bus service operating on University Avenue (routes 16 and 50). There were also savings from reductions to bus service on parallel I-94 (routes 94 and 144). This allowed for an extensive reallocation of bus service hours, which enabled extensive improvements is connecting bus service.

Similar to the Blue Line plan, most bus routes operate very efficiently on 60-, 90-, or 120-min schedule cycles, with most layovers adequate for reliable service. The service plan maximized hours given to providing revenue transit service to the extent possible. Efficient schedule cycles are especially critical during the lower frequency periods. Stakeholders' theme addressed: optimize effectiveness and efficiency to improve productivity.

The Recommended and Final Green Line Plan has also been evaluated in accordance with Federal Transit Administration (FTA) Title VI guidelines to understand its impacts on low-income and minority populations. This evaluation finds that the recommended changes do not disparately impact these populations.

Traffic flow around the Green Line was not an issue in the first year of operation, according to researchers from the Minnesota Traffic Observatory at the University of Minnesota.

The April 2015 *Catalyst*, Center for Transportation Studies, University of Minnesota, published the findings in an article titled Green Line Light-Rail Corridor: New Model Helps Analyze Congestion Impacts on Nearby Roads, reprinted here:

> "The Green Line, which connects Minneapolis and Street Paul, opened for service on June 14, 2014. Findings from the new model indicate that I-94 absorbed most of the vehicle traffic diverting from University Avenue—which the Green Line runs along for most of its route—but freeway speeds were not significantly lowered. Neighboring roads were also affected, but the added traffic burden did not spread far from the LRT route. In addition, some parts of the Twin Cities metropolitan area, including downtown Street Paul, saw some improvement in congestion. For example, average speeds on downtown Street Paul streets increased by 10 to 15% during the afternoon peak period."

Traffic signal delay was a significant problem for on-time performance of the Green Line in the first few months of operations. Unlike the Blue Line, which benefits from traffic signal preemption at most intersections outside of downtown Minneapolis, the Green Line relies on compatible traffic signal progression to minimize delays at intersections. Delays close to 10 min were common, badly reducing the quality of the transfer connections with buses and with the Blue Line. There are 63 signalized intersections on the Green Line, 35 of them between the two downtowns. Happily, after extensive testing and adjustment of the signals, the on-time performance of the new line has improved to the point that the 45- to 46-min terminal-to-terminal running time is now being achieved by almost all trips every day.

The METRO Green Line was projected to provide an estimated 13.2 million annual rides by year 2030, and ridership models estimated that about 40% of METRO Green Line customers will ride bus service to stations. These long-term goals appear to becoming potentially near term goals. Projected annual rides for the METRO Green Line for year 2015 are about 10.5 million so, if the early trend continues, the year 2030 goal may well be realized by year 2020. Bus ridership is lower, as expected due to shifts to the METRO service; however, even accounting for this fact there are about 14,000 or 18% new rides per day as a result of the METRO Green Line and connecting bus service.

CONCLUSIONS

- As of 2015, the METRO lines and their connecting bus service have succeeded in attracting close to 41,000 new daily rides to a growing Twin Cities transit system.
- Metro Transit successfully redesigned bus service around the new METRO LRT lines.
- The redesigned bus services' frequencies and span maximized convenient transfer opportunities bus–rail and bus–bus seven days a week.
- The service plans maximized hours given to providing revenue service through the use of efficient route lengths and schedule cycles.
- Neighborhood-to-neighborhood mobility has improved through an expanded crosstown network that filled service coverage gaps.
- Parallel local bus service is retained only in the segments of the corridors where they are most needed.
- Off-street bus loops were required only with the METRO Blue Line to accommodate terminating bus routes.

- Metro Blue Line's two park and rides are about half full but attract riders from much greater distances than originally expected.

LESSONS LEARNED

- Solicit input from all stakeholders regarding their travel needs before developing a plan.
- Do not depend completely on a formal public outreach process. Be willing to gather input at many small less formal meetings.
- Locate METRO stations very close to established bus stops or directly accessible from nearby bus routes.

NOTES

1. The pre–Blue Line bus operations and ridership are outlined in detail in the Sector 5 Existing Conditions Report. This report documents ridership collected at every bus stop in the sector. The report is available on request.
2. See a complete description of changes in the Central–South (Sector 5) Final Transit Plan. The report is available on request.
3. The pre–Green Line bus operations and ridership are outlined in detail in the Central Corridor Transit Service Study Existing Conditions Report. This report documented development patterns, major attractions and destinations in the area, and current and future travel patterns. The report is available on request.
4. The Trusted Advocate Report is available on request.
5. See a complete description of changes in the Central Corridor Transit Service Study Final Plan Report. The report is available on request.

Infrastructure Developments

Block Rail
Current Best Practices and Experience on Recent Projects

LUCAS L. OLSON
HDR Engineering, Inc.

The following paper discusses the current state of the practice for implementing a domestically produced block rail designated as 112TRAM rail. This rail was installed in Portland, Oregon, in 2011; in Dallas, Texas, in 2013–2014; and in Kansas City, Missouri, in 2014–2015. It is the only domestically produced grooved rail that meets the Buy America requirements of the Federal Transit Administration (FTA). The 112TRAM rail has become the preferred rail section for cities and transit agencies installing embedded track with a steel flangeway and is planned for installation in Milwaukee, Wisconsin, and Seattle, Washington, within the next few years. This paper also discusses how block rail came to the U.S market, where and how it is made, and how the rail works with other trackwork such as turnouts and insulated joints.

INTRODUCTION

What Is Block Rail?

Block rail is a "webless" rail section specifically designed and used for tramways in Europe and now is in use in the United States. It is less than 3 in. tall and used for light duty track such as streetcar or light rail and is continuously supported in a concrete slab or precast panel (embedded track) (Figure 1).

FIGURE 1 A stack of block rail.

Why Was It Introduced to the U.S. Market?

Because of a desire to support domestic manufacturing, FTA and the current administration have increased pressure to comply with Buy America requirements. FTA has made it clear that nondomestically produced rail and trackwork products are no longer permitted for federally funded transit projects. This includes the foreign manufactured girder rail traditionally used in many modern streetcar and light rail transit systems across the United States.

Why Do U.S. Mills Roll Traditional Girder Rail Versus Block Rail?

Because of the shape of the girder rail, it requires a universal roller to create the shape and meet the industry tolerances. The current market demand for a grooved rail section (girder or block) does not justify the upfront investment costs it would take for a mill to purchase the equipment to roll girder rail. In addition, the production rate of producing girder rail is much lower than the traditional tee rail and not as profitable to roll, even if a mill were to have the proper equipment and technical capability. However, because of the simple shape of block rail, it can be rolled with the same existing equipment in most U.S. mills and requires only a modest investment of adding new rolls to be milled to the shape of the block rail.

Where Is the Rail Going to Be Rolled?

ArcelorMittal, of Steelton, Pennsylvania, completed the first production rolling of block rail in June 2011 for Portland Streetcar's Moody Avenue double-track project. ArcelorMittal took lessons learned from a "sister" mill located in Chorzow, Poland, that currently rolls a block rail section called LK-1 (similar to the U.S.-made 112TRAM). The mill has since rolled 112TRAM rail for both Dallas and Kansas City that totals approximately 15 linear miles of rail (Figures 2 and 3).

FIGURE 2 Block rail being rolled.

FIGURE 3 Block rail cooling after rolling.

What Is the Anticipated Lead Time for Block Rail in the United States?

ArcelorMittal rolls the 112TRAM rail in its specialty mill, a facility specifically designed to roll lower-quantity (similar to light rail transit or streetcar projects) and specialty-section orders. Because of this, it is not difficult to fit in a rolling for the 112TRAM, and lead times are typically 4 months or less.

What Is the Rail Called?

The rail has been designated as 112TRAM, which stands for 112-lb per yard tram rail ArcelorMittal. The rail section has been designed to closely match the shape of the LK-1 tram rail used in Europe, but with a few modifications, so that it is more universal and will work with transit systems that have installed either 51R1 or 53R1 European girder rail sections. The main difference between 112TRAM and LK-1 is the flangeway dimensions. The 112TRAM rail has been designed with a slightly wider and shallower depth flangeway similar to 51R1 European girder rail (Figure 4).

CURRENT BEST PRACTICES

How Is It Installed?

Block rail has been installed in a similar manner to girder rail or tee rail that is embedded in concrete. It is installed in a rubber boot specifically developed for the block rail. The rail will be set to line and guage using sacrificial gauge ties with special clips to hold it in place until the concrete is poured and set. The first installation of block rail in Portland was a “proving” ground that provided valuable lessons learned that were later applied in Dallas and Kansas City. The original Portland design included a riser on the gauge tie (or “chair”), which did not allow for enough pressure on the toe of the rail to hold it solidly in place during the concrete pour. This

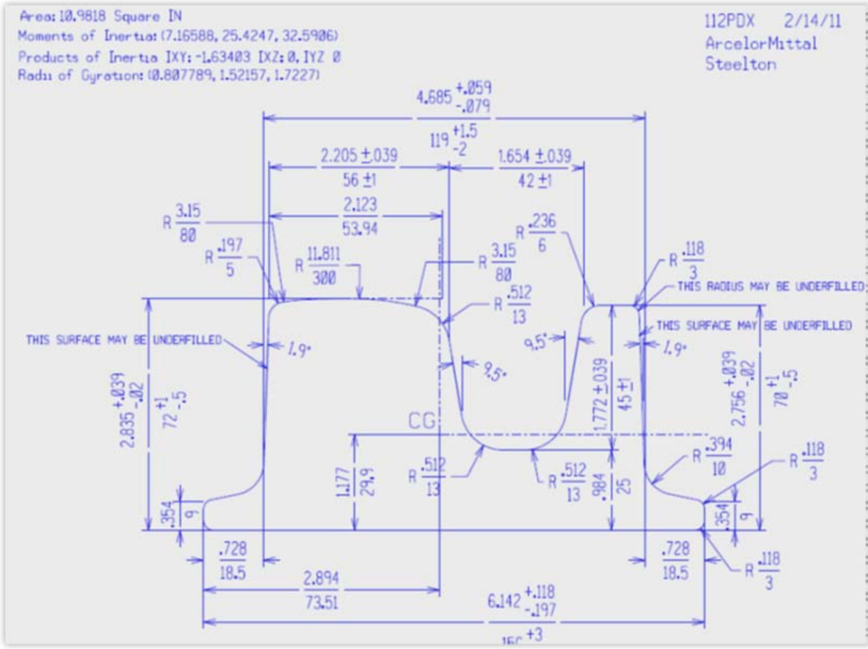


FIGURE 4 112TRAM rail section.

resulted in the contractor coming up with another "jig" that maintained gauge during construction. This issue was addressed in Dallas by making a gauge tie out of two angle iron pieces welded 4 in. apart. This modified gauge tie assemply allowed for the ties to be closer to the concrete surface and created the opportunity for the rail clip to hold the rail in place without additional jigs (Figure 5). Kansas City took a different approach with a narrower gauge tie, which also allowed it to be placed closer to the pavement surface. Figure 6 is a photo of the installation of 112TRAM block rail in Kansas City.

FIGURE 5 112TRAM embedded track: Dallas.

FIGURE 6 112TRAM installation: Kansas City.

What Are Considerations for Current and Future Projects?

The 112TRAM rail has already been installed in Portland and Dallas, which are both operational, as well as in Kansas City, which will be complete with track installation in 2015 and start operations in early 2016. It is also the selected rail for the Milwaukee Streetcar, which is currently in the final design stages as well as for two extensions to the streetcar line in Seattle. Other agencies and cities are also considering block rail for their embedded rail track sections.

What About Other Trackwork Materials?

Other trackwork materials such as turnouts, insulated joints, and transition rails have been adapted to work with block rail. Below is a summary of some of the track work elements.

Turnouts

There are no domestic suppliers of girder rail or European style turnouts as well as no domestic manufacturer of block rail turnouts (at the time of this paper). To date, all turnouts planned for systems with block rail that must meet Buy America standards have been tee rail turnouts. Transition rails have been developed to transition from the 112TRAM to 115RE (or other rail sections) to allow for 115RE (tee rail) turnouts. In a program under development, one U.S. manufacturer is working with its European partners to bring the designs and technologies used to produce block rail turnouts in Europe here to the United States. It is not clear when this manufacturer will start bidding on projects, but it could be as soon as 2015.

Transition Rails

One U.S. manufacturer, VAE Nortrak, has produced transition rails from 112TRAM to the 115RE rail section. This is done using a solid piece of steel and milling the shape of the transition from the 112TRAM rail section to the 115RE rail section.

Welding

The 112TRAM rail can be welded by using either thermite (field) welds or flash butt welds. Portland used 100% field welds for the initial installation while Dallas and Kansas City have both used primarily flash butt welding to produce long strings and used thermite welds only to connect the strings together in their final location. So far, no issues out of the ordinary have been reported with either welding process.

Insulated Joints

VAE Nortrak has developed a block rail insulated joint used in Portland, Dallas, and Kansas City. As yet, it has not failed (pulled apart), but additional research and development are under way.

CONCLUSION

In the past 4 years, the development of block rail in the United States has seen major advancements. These include techniques and advancements in manufacturing products that have addressed many of the issues experienced in the original installation. With the growing popularity of block rail, the industry continues to evolve, and new manufacturers of trackwork products look to enter the market. Over the next several years, long term maintenance and durability will be tested, and results can be reported. To date, block rail has proven to be a good alternative to the foreign-made girder rail that is no longer available for federally funded projects in the United States.

Transit Signal Priority Implementation in Phoenix

JAY YENERICH
Valley Metro, Phoenix, Arizona

BACKGROUND

Significant improvements have been made to the Phoenix, Arizona, metropolitan area's transit system over the last 15 years as a result of local and regional sales tax initiatives. Chief among the improvements was the 20-mi, predominantly in-street, light rail transit (LRT) system, which was planned, designed, and constructed during this time. The purpose of the LRT project was to connect several major employment centers, residential areas, universities, grade schools, the region's airport, and numerous special event facilities. This required careful planning and route choice to optimize ridership and minimize impacts. It was decided to take advantage of Phoenix's well-defined grid pattern of streets, and the logical choice for the LRT route was in the middle of key arterial streets, which allowed for parallel streets to absorb the diverted traffic.

PURPOSE

Most of the 20-mi system was planned, designed, and constructed in the confines of existing streets in the cities of Phoenix, Tempe, and Mesa, Arizona. This caused the system to transverse 150 intersections. During the planning stage of the project, these cities raised concerns that delays to cross-street traffic would be great, and they were also concerned for the safety of motorists crossing the line's path. Valley Metro desired to maximize operating speed and minimize delays for the trains. Therefore, a unique traffic signal system was needed to attain these goals.

METHODS

These goals were achieved through a comprehensive traffic signal control strategy called predictive priority. Predictive priority allows for the signal system to make adjustments in the traffic signal cycle in response to advanced calls from approaching trains. A peer-to-peer fiber-optic network was built to allow for the exchange of data. Local detection of the trains was converted to a call to intersections further downstream.

RESULTS

Cascading peer-to-peer calls allow the train to progress without unplanned stops between stations at traffic signals. The Valley Metro light rail system has been in operation for 6 years. Modifications to the signal system have been made as traffic demands and safety issues have arisen. However, the essential properties of the predictive priority system have not changed and still perform well to this day.

CONCLUSION

When planning began on the Valley Metro light rail system, there were concerns about meeting all the demands of implementing an in-street rapid transit system. The predictive priority system addressed all the concerns, and it continues to perform as expected, providing safe, reliable service while not adversely affecting vehicular traffic. Valley Metro is preparing to open up six more LRT miles during the next year, and a similar predictive priority system will be provided for the added 40 intersections.

INTRODUCTION

A well-planned transit system can reduce the rate of growth in urban congestion, improve air quality, and provide an impetus to the economic growth of the region. During the previous decade and a half, the residents, city planners, and transit agencies of greater metropolitan Phoenix made a conscientious effort to improve transit mobility throughout the region. One of the keys in the Phoenix project to make transit a viable transportation alternative for commuters was an intersection management system that ensured competitive transit travel time without degrading vehicular travel time beyond acceptable levels.

This goal was achieved by providing priority for the transit vehicles at the signalized intersections. Transit signal priority systems had been installed in Houston, Texas, and in Salt Lake City, Utah, before the Phoenix starter system, which transverses Phoenix, Tempe, and Mesa. Lessons learned from the previous systems were applied as well as the logic and methodologies.

The Valley Metro light rail system developed a comprehensive traffic signal control strategy called predictive priority for the Central Phoenix–East Valley LRT project. The new LRT line was 20 mi long, and 18.8 mi were in-street with 150 intersections. The existing and proposed future LRT lines are represented in Figure 1. Most of the extensions will have similar characteristics and run in the middle of existing roadways, except the Capitol–I-10 Corridor, which will run in the freeway right-of-way.

CENTRAL PHOENIX–EAST VALLEY LRT PROJECT

The Valley Metro LRT comprises 20 mi of an LRT line connecting the cities of Phoenix, Tempe, and Mesa. The alignment was in a grid network of surface streets with coordinated signal operation. The light rail vehicles (LRVs) operate in their exclusive right-of-way adjacent to vehicular traffic, except at the intersections where they operate on shared right-of-way controlled by traffic signals. For the introduction of the Valley Metro LRT system, 150 intersections were rebuilt and their operation modified. Each city had a variety of communication media, including twisted pair, fiber-optic, and T1 telephone systems, and also had different central control systems. One common feature was that all three cities used older National Electrical

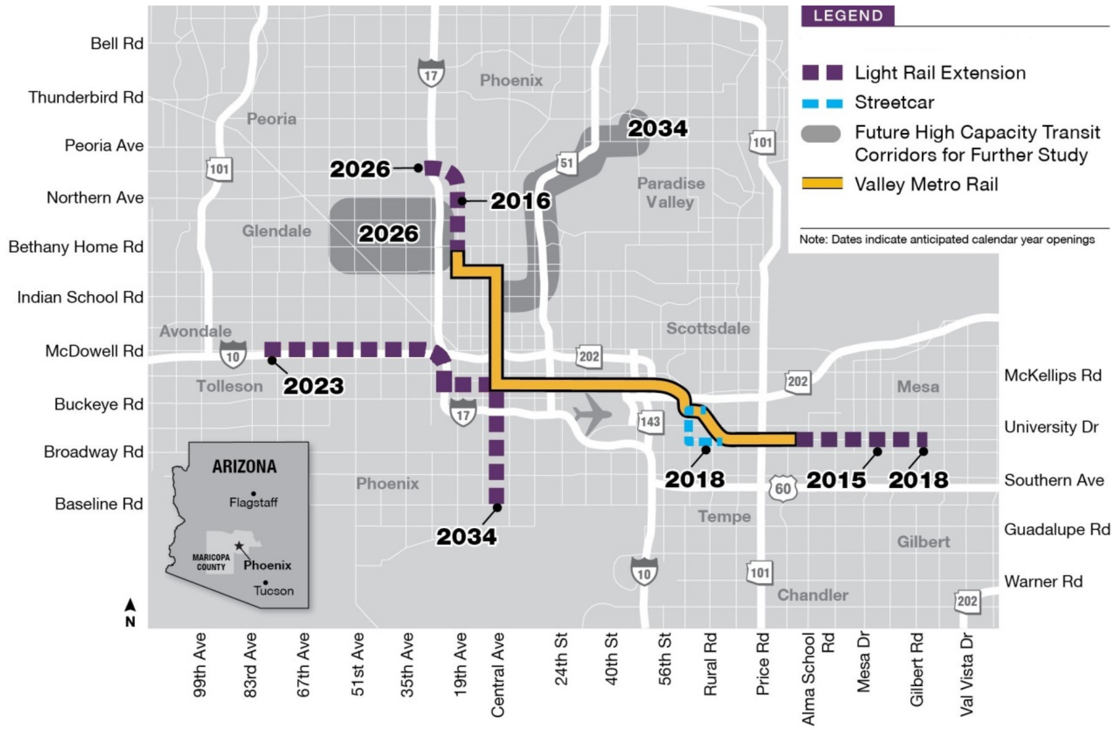


FIGURE 1 Future and existing LRT lines in the Phoenix area.

Manufacturers Association (NEMA) TS-2 traffic signal controllers. The project resulted in development of a unified Ethernet-based communication system connecting all cities.

DEVELOPMENT OF SIGNAL CONTROL STRATEGIES

At the onset of the project, several traffic signal control strategies were conceptualized. These strategies are described below.

Signal Coordination

Signal coordination provided for the sequencing of green signals along a corridor to allow for the movement of traffic with the minimal number of stops. Two different scenarios were evaluated. In the first case the signals were coordinated for vehicular traffic, and in the second case, they were coordinated for the LRVs.

Full Preemption

Preemption would provide for the immediate servicing of a transit phase when a transit vehicle was detected approaching an intersection. The transit vehicle was serviced by terminating all conflicting vehicular phases. Preemption provided the LRT with the best travel time but was unacceptable for vehicular traffic because of impacts to vehicular signal coordination.

Transit Priority

These strategies included providing either an early green, or an early green and a green extension, for the transit phase. The additional green time for the transit phase was obtained by reducing the splits for the minor movements. Since minor movements were not compensated for the time lost, this adversely affected the level of service of the intersections.

Predictive Priority

Predictive priority allows the LRV to get a green signal at intersections on the basis of systematic tracking of the vehicle with a series of advanced detectors embedded in the trackway. The signal controller then has the ability to provide an early green or a green extension for the transit phase, adjust the phase split time, or adjust the coordinated offset value. The signal controller decision would be based on projected LRV arrival at the intersection. This was the only method evaluated that allowed trains to operate through signalized intersection crossings with acceptable LRV travel times and vehicular delay on all legs of the intersections while maintaining coordination within the traffic signal system.

It was known at the onset that relying on only signal coordination would not be used. To prove which type of control would best suit the needs of the project, a test section of the alignment from Earll to McDowell was developed. Table 1 demonstrates a summary of results. The results showed that the majority of the items favored predictive priority, and so it was selected.

HARDWARE: CUSTOMIZED SIGNAL CONTROLLER

However, a question remained: On which platform should the predictive priority system be placed? Although signal controllers have evolved significantly over the years, two standards remain. The NEMA standards included the NEMA TS-1 and TS-2. Another set of standards developed by the California Department of Transportation and the New York Department of Transportation led to the development of the Model 170 and later the Model 2070 traffic signal controllers.

The most significant difference between the NEMA standards and the Model 170 and 2070 standards had been the open architecture of the hardware. In the NEMA standards, the hardware and the software were integrated. Often there was incompatibility between NEMA controllers from different manufacturers. The Model 2070 controllers were similar irrespective of the manufacturer, because the standards specify the hardware configuration. Several signal software packages can be implemented with these controllers.

TABLE 1 Comparison of the Priority, Functionality, and Costs

	Full Preemption	Transit Priority	Predictive Priority
Average delay (s)	27	23	28
Average queue (ft)	251	191	159
Average LRT travel time (min)	6.2	7.8	6.0
Average vehicular travel time (min)	4.5	4.3	4.6

NEMA Controller

A NEMA controller in the early 2000s could operate bus transit priority operations but was not capable of implementing predictive priority control. This was primarily because the NEMA controllers at that time did not support sufficient features, including memory on the motherboard, to implement the predictive priority logic.

Model 2070 Controller

VS-PLUS software was used to demonstrate predictive priority with the 2070 controllers. VS-PLUS had been used in Europe but had seen limited applications in the United States. One of the hurdles in the use of the 2070 controllers was that they were not being used in the Phoenix area. Although the 2070 controller had the capability to replicate the predictive priority control, it was incompatible with the existing NEMA signal controllers and the central systems at the traffic operations centers for the cities.

Replacing all controllers along the LRT alignment with 2070 controllers was not an option. Doing so would have resulted in two separate systems and cause operational and maintenance problems for the traffic engineering divisions of the cities. With more than 1,000 signals in Phoenix, 400 in Mesa, and 250 in Tempe, replacing all controllers in the cities with 2070 controllers would have been a mammoth task and was not financially feasible in that it would have resulted in an enormous increase in the project budget.

The Solution

A request for proposal was sent to Econolite, the manufacturer of the cities' NEMA controllers, asking for solutions. Econolite offered two solutions:

1. Rewriting its existing software to facilitate predictive priority on a new platform.
2. Engineering a new controller so that either processor could be used (NEMA or Model 2070). By inserting a 2070-1BCPU module, a controller would function as a 2070 controller. When the 2070-1B was not used, the controller would function as a standard NEMA controller.

The second solution was chosen; it had less developmental risk to the project, and off-the-shelf predictive priority software could be used. NextPhase signal control software (discussed later), developed by Siemens Intelligent Transportation Systems, was selected for this project. At the time, NextPhase was fairly new but had seen successful deployments for the Salt Lake City and Houston LRT systems. In addition, Econolite developed an input menu that looked and felt more like ASC/2 to give the local agencies the familiarity of their existing systems.

SOFTWARE: PREDICTIVE PRIORITY TRAFFIC CONTROL

Predictive priority provided an adaptive traffic signal control strategy that let the LRT trains "adjust" the traffic signal's normal sequence of phases (Figure 2). The controller enables a green

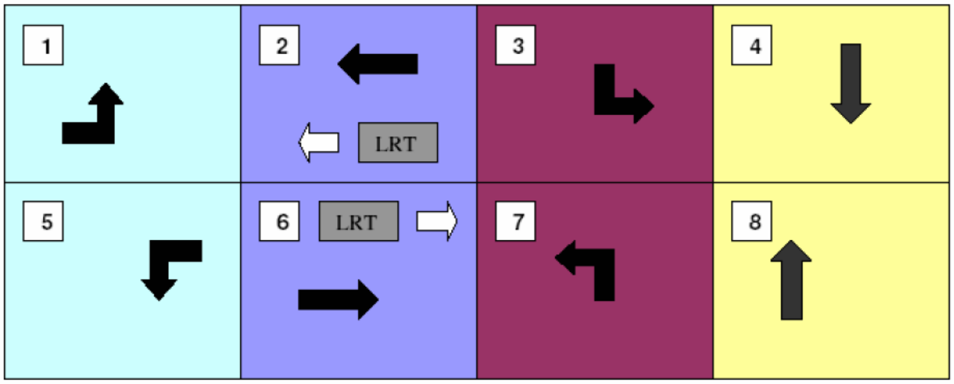
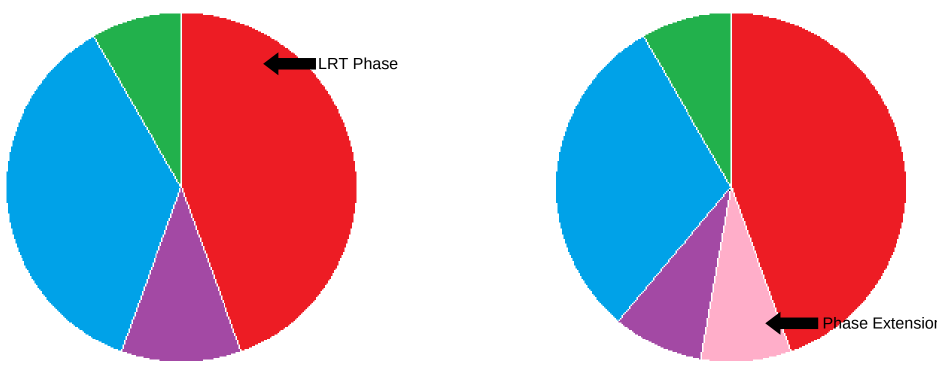


FIGURE 2 Standard traffic signal phase sequence chart.

signal for the LRV at intersections so that it can proceed without stopping or slowing at stations waiting for the signal to change.

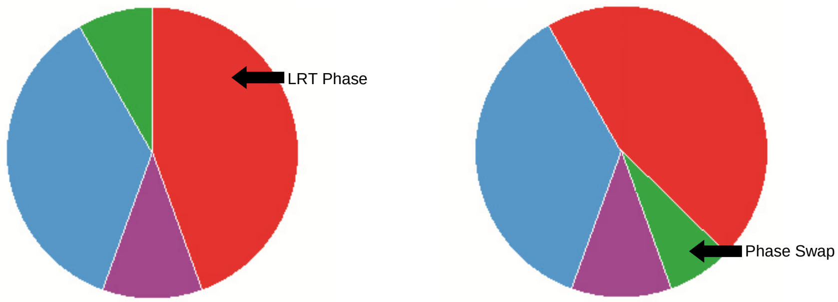
In this signal control strategy, the basic traffic signal background cycle was maintained but with the changes made to the length and sequencing of the phase splits to allow the phase serving LRT trains to be extended or advanced (Figures 3 and 4). This was made possible by LRT detectors embedded in the trackway that signal the arrival and departure of a train at intersections.

The signal controllers were connected to each other through a peer-to-peer communications network, so this information was also communicated to several intersections downstream, and gave those controllers enough time to adjust phase splits by predicting the arrival of the LRT at the intersection. This phasing allows only small portions of time to be adjusted so that it does not interfere unacceptably with cross-street traffic or pedestrian movement.



(a) **(b)**

FIGURE 3 (*a*) Base cycle with train estimated to arrive at end of through phase and (*b*) through phase extended to allow passage of train. Colors correspond to phase splits as shown in Figure 2.



(a) (b)

FIGURE 4 (*a*) Base cycle with train estimated to arrive during the cross-street phase and (*b*) cross-street phase terminated early and LRT phase served and followed by left-turn phase.

COMMUNICATIONS

Communications between intersections was the key element for the successful implementation of a predictive priority signal control system. Consequently, Valley Metro designed a backbone gigabit Ethernet network. This network was designed as a distributive intelligent network. Unlike a network with only central computing capabilities, a failure will not cause the entire system to stop working. Computations to be performed using centralized control would be enormous. The system would have to keep track of all detector inputs and send out information to every controller. Figure 5 shows a conceptual architecture of the proposed network.

With distributive control, the traffic controllers at the intersection manage the operations of that intersection on the basis of the input from adjacent intersections about train location,

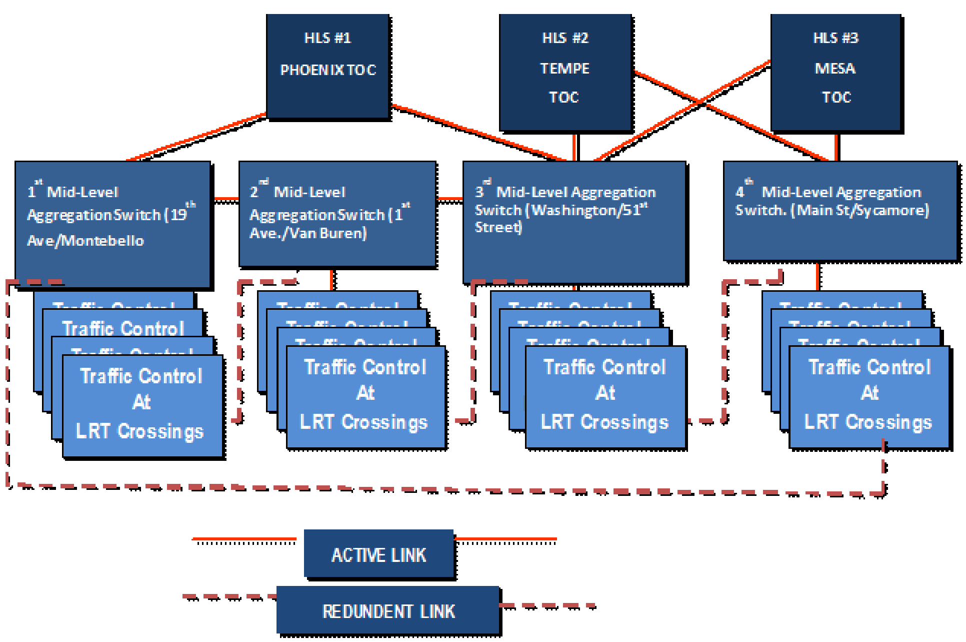


FIGURE 5 Design of backbone gigabit fiber-optic Ethernet network.

speed, and projected arrival time. However, the system can still be managed from a central traffic management center.

Valley Metro's design consisted of six to eight controllers per channel to form a daisy-chain network. The controllers at the end of the chain were connected to different mid-level switches to create a self-healing switched network.

CHALLENGES

Challenges are always expected on projects. This was particularly true for this complicated project. It was a new transit line through three municipalities and encompassed 8 years of alternative analysis, environmental impact studies, preliminary and final design, and construction and commissioning. Consequently, challenges were found throughout all phases of the project. The initial selection of both the hardware and software was the first challenge for transit signal priority development. Institutional buy-in was the biggest hurdle because of the desire to maintain the same controller type while still achieving increased functionality.

Since this was a new combination of equipment by the manufacturer, there were numerous revisions to the software versions. NextPhase 1.5.5d had been deployed in Salt Lake City in 2001; however, it was developed to run from the central system. By opening day in late 2008, almost 20 minor and major revisions of the software were completed. The main reason for the revisions stemmed from the desire for distributive intelligence and having the communications port data reside on the same processor as the native program. With increased Ethernet traffic on the same port, the program could become overloaded and cause the timing to become unstable. This, in turn, could cause the conflict monitor to send the intersection into flash condition.

Another major hurdle was the communications network. During commissioning, the municipalities decided to change the network architecture. They requested separate but communicating networks, which required splitting the network into two subnetworks using a network router. The router allowed seamless communication between field level devices, but restricted control and monitoring of the devices to the central systems of the respective cities only. This resulted in a more efficiently managed network with protection from excess Ethernet traffic.

TRAFFIC SIGNAL INTEGRATION AND TECHNOLOGY TRANSFER

A traffic signal test facility was set up for the project so that all traffic signal control equipment could be tested and configured before installation. Figure 6 provides a photo of the test facility. The tests included hardware, firmware, and communications equipment testing.

Each traffic signal controller was custom programmed for the intersection at which it would eventually operate. This included setting up the signal timings for all the controllers and implementing the priority control settings for each.

One hundred and sixty cabinets and controllers were tested. The bench testing occurred over a period of 2 years. The testing included installing all of the detector cards, controllers, wiring (system development life cycle and power plugs), load switches, and bus interface units.

FIGURE 6 Testing of traffic signal controllers and cabinets at the test facility.

Once installed, the cabinets were tested for a week as eight phase traffic signals with LRT logic. Any faulty equipment was removed and sent back to the manufacturer. Lastly, the cabinets were then configured for the intersection at which they were to be placed and tested again. Five contractors would coordinate the retrieval of specific cabinets dedicated for specific locations when underground conduit and foundations were ready. The project benefited from having the controllers and cabinets preconfigured for the precise location at which they needed to be installed. This kept the traffic signal installation and integration schedule on time and ready well in advance of any train testing.

A detailed technology transfer program was developed and implemented for the traffic signal operations and maintenance personnel of the three cities. The program included additional classroom training sessions on the hardware and firmware used in the controllers and weekly hands-on training sessions at the test facility. This program helped the operations and maintenance personnel to manage the steep learning curve in adopting the new system.

FUTURE DEVELOPMENTS AND CONCLUSIONS

The story in the Phoenix region is still ongoing. Two 3-mi extensions are currently under construction that will both open during the next year. In addition, corridor studies are under way to develop high capacity lines south of downtown Phoenix and west of downtown Phoenix along the I-10 corridor as well as a route that is planned to come from downtown Glendale to the existing line.

The Phoenix region plans to expand its transit system over the next decade and beyond. With excellent ridership and the backing of stakeholders, the Phoenix area transit system will continue to grow and serve more people. Just 15 years ago, high capacity transit was nonexistent. The area has come a long way in expanding and improving its transit networks in just a short time, helped significantly by the implementation of transit signal priority systems.

PANEL DISCUSSION

Successful Streetcar Design in Motorized Cities

Best Practices from Western and Eastern Europe

RandstadRail

From a Traditional Tram System to an Integrated Tram and Light Rail System in the Metropolitan Region Rotterdam–The Hague

LEONARDUS H. HARING
HLR Consultancy, the Netherlands

Tram operation in The Hague started in 1864. After World War II (WWII) the tram system in The Hague was deteriorated, but the city decided to retain and improve the system. The city closed underused lines and made extensions of tram lines to many new residential and business districts in The Hague and suburbs. For the connection with the satellite city Zoetermeer, a heavy railway line was built.

After a period of decline in the 1960s, the tram system became more and more important in order to cope with the consequences of developments in The Hague and the growing urbanization of the region. This region is strongly connected with the Rotterdam region, which means that public transport in these regions should be integrated.

The urbanization of The Hague, Rotterdam, and Zoetermeer required an appropriate light rail system. To establish the RandstadRail system, two railway lines between the cities were converted to light rail and integrated with the tram in The Hague and the metro in Rotterdam. This system started operation in Rotterdam in 1968.

The Hague decided to adapt the tram system to the developments in the city and region. Because of the flexibility of tram and light rail, The Hague's tram system formed the basis of an integrated tram and light rail system serving the city and the region and was strongly connected with the Rotterdam region. The Hague's tram system is not a separate system anymore, and its future is determined by the recently established Metropolitan Region Rotterdam–The Hague (MRDH).

INTRODUCTION

This paper provides an overview of development of the tram system of The Hague since WWII. The system is operated by HTM, a privatized public transport company, currently owned by the City of The Hague and Dutch Railways. In the past The Hague and HTM were responsible for all developments of the tram system, including financing.

The Hague is the seat of the Dutch government and the capital of the province of South Holland. With a population of 515,880 inhabitants and more than one million inhabitants, including the suburbs, it is the third-largest city in the Netherlands after Amsterdam (the capital of the country) and Rotterdam.

Rotterdam is a city 20 km south of The Hague located within the Rhine–Meuse–Schelde river delta at the North Sea; it is home to Europe's largest port and is the 10th largest port in the world. The port is successful because of this strategic location. The rivers give waterway access into the heart of Western Europe. Rotterdam has a population of 624,799.

The MRDH (Figure 1) has a population of approximately 2.7 million and is the most populous in the country. Some statistics follow:

- Surface: 990 km^2
- Inhabitants: 2,260,000
- Residences: 1,000,000
- Employment: 1,000,000
- % of Dutch gross national product: 26

Because of the demographic, political, and administrative developments in the region of The Hague and the neighboring region of Rotterdam, the transport authority of the MRDH with 22 other municipalities was established in January 2015. The MRDH is responsible for mobility in general (all traffic and transit modes) in the southwestern part of the province of South Holland.

This paper gives an overview of major developments in the city and region of The Hague, the relation with the Rotterdam region, and how these developments influenced the development of the tram system in The Hague and surrounding region. The overview is mainly based on HTM and The Hague municipal documents.

FIGURE 1 Metropolitan Region Rotterdam–The Hague.

THE HAGUE TRAM SYSTEM, 1945–1960s

The tram systems in The Hague and Rotterdam encountered serious problems after WWII. Both cities were seriously damaged by war activities:

- The city center of Rotterdam was bombed by the German Luftwaffe and almost completely destroyed in May 1940 to order to force the Netherlands to surrender to the German forces.
- The coastal area of The Hague partly was destroyed by the construction of the Atlantic Wall and bombardments by allied air forces in March 1945 in the area north of the city center.

Passenger demand was very high in the first years after the war (118.4 million in 1948) because other means of transport were not available. There was also a lack of trams and proper rail infrastructure. Trams confiscated during the war were returned from Germany to The Hague. Some of these trams could be repaired, and others were scrapped. Many kilometers of track needed repair.

By the end of the 1950s, private traffic had grown substantially, and the use of public transport declined. The tram became outdated, and many city tram lines were closed. In 1961 two regional tram lines to Leiden and Wassenaar were closed. The railway between The Hague and the suburb of Scheveningen, a fishing harbor and seaside resort on the North Sea coast, was closed in 1953 as well. The tram to Delft survived because of its car with one-man operation designed by the then Presidents' Conference Committee (PCC).

Despite some renovations of the tram system after WWII, it was necessary to find effective solutions for growing traffic problems. Finally, the city decided not to liquidate the tram but to find solutions for how the system could be adapted to the needs of the developing city. The tram system could be described as follows:

- In 1948 the (double) track length was 101.4 km.
- In 1963 the tram network had a total length of approximately 75.7 km.
- A total of 43% of the network was on segregated tracks.

POPULATION DEVELOPMENT

After WWII the tram system was strongly influenced by the demographic developments in The Hague. The population was growing, but there was too little space for expansion because of the location on the North Sea coast. The required space for housing was very high. In 1962 the government decided to convert the village of Zoetermeer (east of The Hague) with 6,000 inhabitants to a satellite city. Currently Zoetermeer has 125,000 inhabitants.

In the mid-1960s the government decided to move governmental services and 15,000 employees and families from The Hague to regions in the country with serious economic problems. This policy was not very successful and was abandoned in the early 1980s.

Between 1960 and 1980 the population of The Hague was reduced from 600,000 to 440,000. The city suffered from reduced investments in housing and deterioration of the inner city. In the mid-1970s there was lack of space for 15,000 residences, which increased to 80,000 in the 1980s. Suburbanization was inevitable. Many people left The Hague and moved to the suburbs.

After 1980 the population was growing again to more than 500,000 as a result of urban renewal and new residential areas with 20,000 residences south and east of The Hague (Vinex districts) in former agricultural areas and a former air force base. Additional growth of another 60,000 to 80,000 is expected in the next decades.

The city center became more popular for leisure activities and shopping and developed into an important office district that included Dutch ministries returning from the suburbs. The urbanization of the region is illustrated in Figure 2.

Large traffic problems were caused by the increasing number of commuters, private car use (due to higher wealth), and reduced use of bicycles and public transport. Many plans were made for roads and extensions of tram lines to new residential areas and a new commuter railway to Zoetermeer. Also, the growing urbanization in the area between The Hague and Rotterdam required solutions for improving mobility.

A NEW FUTURE FOR THE TRAM, 1963–1966

In 1963 the municipality of The Hague and the owner of HTM invited a famous German traffic and transport expert, Professor Friedrich Lehner, to make recommendations for the future of public transport in general and the tram system in particular. The main recommendations of Lehner were these:

- Underused tram lines should be closed,
- Lines with high patronage should be bundled,
- Trams operated on segregated tracks should be the main carrier to new residential areas, and
- Old rolling stock should be replaced.

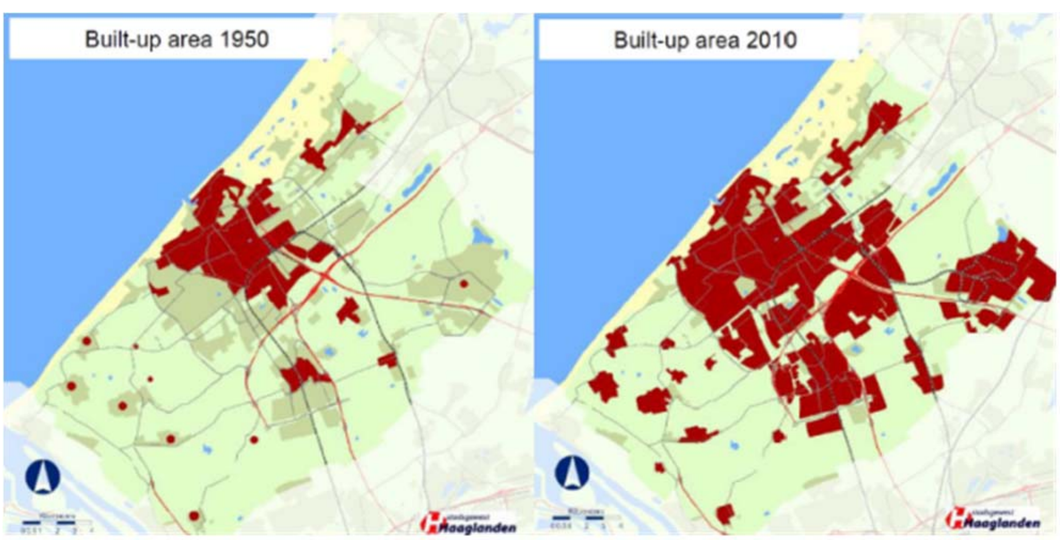


FIGURE 2 Urbanization in The Hague region.

In The Hague there was a good balance between improvement of public transport and development of a proper road network (no influences of automobile–highway lobbies): the tram should be the back bone of public transport to serve the newly developed postwar residential districts in The Hague southwest and the suburbs of Rijswijk–Leidschendam and should be expanded with a light rail connection to Zoetermeer.

Because of the environmental consequences of a dense bus operation and the more efficient tram operation with large units, Lehner recommended putting surface tram lines in the city center on viaducts or underground, or both, to obtain 100% autonomous tracks. Most important were the tunnels and crossing under the main corridors of Spui and Grote Marktstraat.

The plan was based on the assumption that the number of inhabitants in the region would grow to a level of one million. A large part was executed in 1965–1966 in three phases but did not include the construction of the tunnels. However, because of Lehner's recommendations, the future of the tram was safeguarded.

In the long term Lehner proposed to prepare very heavy corridors for semi-metro operation with tram operation on an upgraded infrastructure. After many discussions the city decided in 1969 to build the semi-metro based on his recommendations. The extensions of the tram system to new residential districts were built in the 1970s and 1980s. These extensions included some converted heavy radial bus lines. The future of the bus system was as a feeder to the tram and to provide tangential connections.

Because of the changes introduced in the HTM network, the track length was approximately 53 km in 1967 with 59% on segregated lanes. In 1968, track length increased to 61.9 km, and in 1979 to 70.9 km, because of extensions to new residential areas. Patronage dropped to 60.3 million per year in 1963, to 48.5 million in 1968, and then increased to 55 million in 1979.

PCC CARS, 1949–1993

Despite the postwar discussions some renovations of tram infrastructure and rolling stock started, including procurement of new trams. After a study in the United States, HTM decided to purchase two PCC cars for testing.

The trams were shorter and less wide than American PCCs and were delivered in 1949. The tests were successful, and HTM purchased another 22 PCC cars from BN (Belgium) for running as single units, which were delivered in 1952 (Figure 3). Between 1957 and 1974 four PCC series followed: 180 2.20-m-wide and 2.35-m-wide cars with driver's cabins and 30 motorized trailers. These vehicles had European-style windows and were fitted with couplers for multiple-unit operation.

Very important tests were carried out with chopper control on five PCCs in order to investigate the reduction of energy consumption and power of substations. Special projects involved the construction of two PCC rail grinders, a party tram, and a PCC for condition monitoring of the infrastructure. Using PCC cars with one-man operation reduced labor costs dramatically. Tram operation with PCC cars ended in 1993, 44 years after the introduction of the first PCC car.

FIGURE 3 PCC 1000 series in city center.

SEMI-METRO

Semi-Metro Network

In 1969 the municipality of The Hague issued a proposal for solutions for the traffic and transport problems. One of the solutions was the semi-metro system proposed by Friedrich Lehner that could be implemented in a few phases. He also recommended light rail to Zoetermeer. Instead a railway was built that opened in 1977 and was operated by Dutch Railways with “Sprinter” trains with high acceleration because of the short distance between the stations.

The first phase of the semi-metro was the construction of a new station at the location of the old existing station with semi-metro lines on top with three branches. The second phase was a tram tunnel under the Grote Marktstraat and the Prinsegracht with a possible extension to The Hague southwest.

The semi-metro plan was abandoned in 1973. The expected increase of employment in the city center was too optimistic, and investments for the tunnel sections were too high. Only the first phase and some parts of the second phase were realized. The tram tunnel under the Grote Marktstraat and the light rail to Zoetermeer were built three decades later.

Semi-Metro Rolling Stock

As part of the semi-metro plan new tram lines were designed on the basis of the dimensions of the future semi-metro light rail vehicles. The semi-metro vehicle would be fitted with trucks from PCC trams. This idea was based on the Chicago light rail fleet that was partly fitted with PCC equipment.

The new vehicles should be 2.65 m wide with a distance of 10 m between the truck centers. A car body construction was selected according to the design of the Bay Area Rapid Transit vehicles in San Francisco and the metro vehicles in Brussels.

FIRST PHASE: SEMI-METRO AND CENTRAL STATION

The tram network in the railway station district close to The Hague city center was highly influenced by the construction of the new Central Station. This station should replace the small old station form 1870 and become a large capacity terminus for railway connections with the eastern part of the Netherlands, the north (Amsterdam) and the south (Rotterdam), and terminus of the line to Zoetermeer.

Simultaneously the redevelopment started at the area north of the station (destroyed in WW II) and the deteriorated area south of the station. Before this redevelopment and the construction of Central Station, the tram system in the area was a traditional surface system comprising city tram lines and three interurban lines.

In September 1973 the first part of Central Station adjacent to the old station could be opened. After demolition of the old station the construction of the new station finally could be finished in 1975.

The Hague and public transport companies wanted to improve public transport connections from the station with destinations in the city and the region and agreed with Dutch Railways to design Central Station as an integrated public transport hub providing easy transfer between train and local and regional public transport systems.

On top of Central Station a large platform was realized with bus stops, a tram station with four tracks, and a turning loop on a parking garage north of the station. The tracks were connected via viaducts and ramps with the tram network south and north of Central Station and included a tram stop on the viaduct. This first phase of the semi-metro was opened in 1976 and replaced all the north–south surface tram lines around Central Station.

For a new rail connection with Scheveningen the tracks on top of Central Station were prepared to make a link with tram lines to this place via a viaduct running through a historical green zone in front of Central Station. This viaduct was not built because of objections from inhabitants of The Hague.

In 2004 the southern ramp of the semi-metro viaduct (+6 m) was connected with the tram tunnel (–12 m) under the main shopping street in The Hague. The viaduct to the tunnel is fully integrated with apartments, shops, and office buildings (including ministries) that were built in the years after the construction of the semi-metro and tram infrastructure.

The tram station was recently reconstructed because of the introduction of the RandstadRail light rail system. The side platforms were replaced by two island platforms (Figure 4).

On the south side of Central Station a tram stop parallel to the railway tracks is located for surface tram lines running from east to west (e.g., coastal area). Figure 5 shows the current tram network of The Hague and, in more detail, the network in the Central Station area.

FIGURE 4 RandstadRail Regio Citadis at The Hague Central Station.

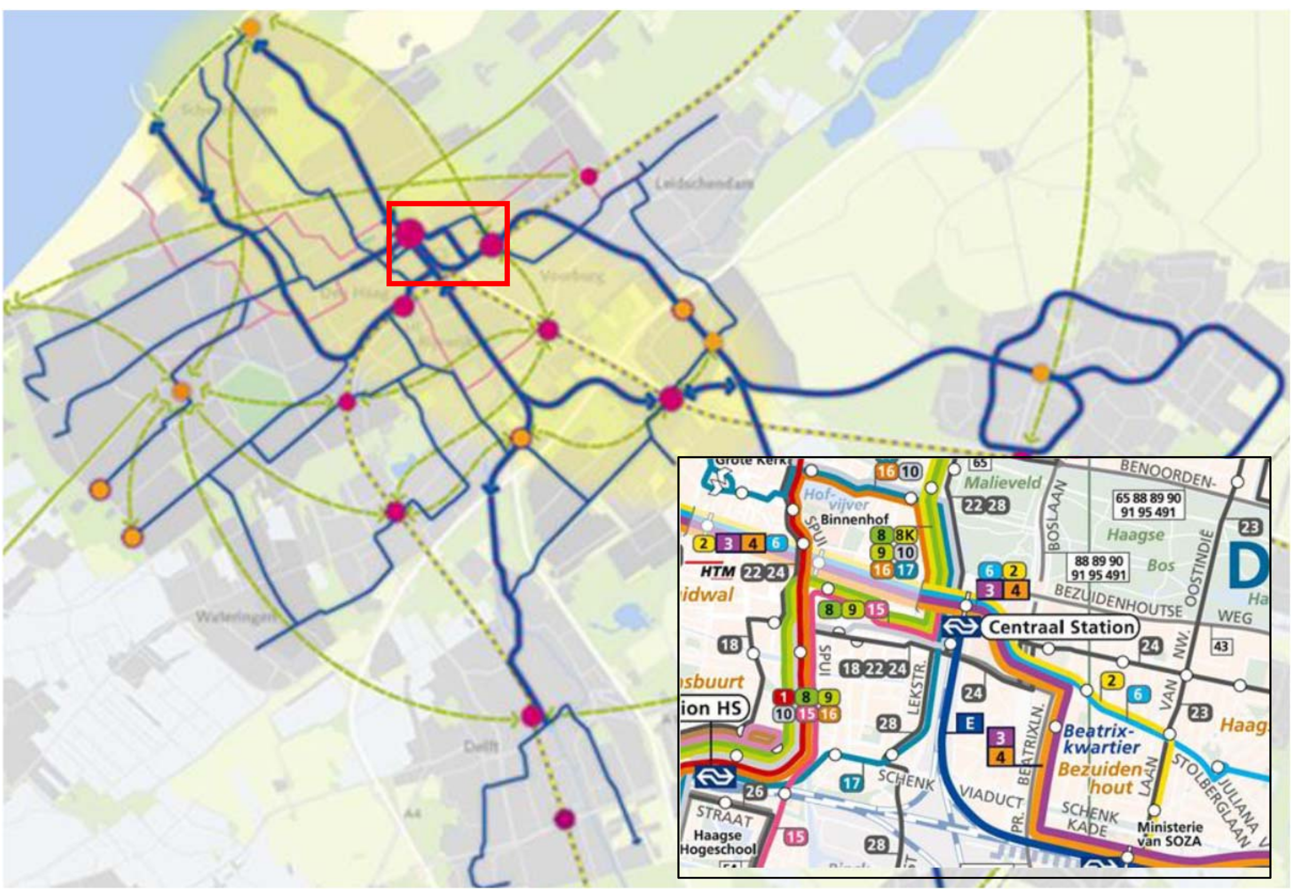


FIGURE 5 Tram and light rail network in The Hague region and Central Station area.

TRAM NETWORK, 1980s–EARLY 2000s

In the 1980s and 1990s many changes were made to improve the quality of the tram system and to provide more connections to newly developed areas. The tram network was growing because of the new tram Lines 15, 16, and 17 to suburbs south of The Hague, the extension of Line 1 from the Delft city center to the southern suburbs of Delft, and the tangential Line 19 from Delft to Leidschendam.

The presented Masterplan Agglomeration network of 1995 was aimed at upgrading of the main tram lines by more segregated tracks and less intersections. The commercial speed should be 25 km/h rather than 18.5km/h. However, the plan was only partly executed with tram Lines 15 and 17 in 1999 and 2002.

Many changes in the tram network were carried out to reduce the costs of operation as required by the central government. However, the length of the network had increased to a 101.8-km network in 2003 with more than 75% of segregated tracks because of the policy to reduce mixed traffic.

Upgrading the infrastructure is an ongoing process aimed at reduction of intersections with other traffic and getting more space for future trams by increasing the distance between tracks centers to increase the structure gauge. For reduction of maintenance and improvement of the environment (e.g., noise and vibrations), different rail constructions for street track, grass track, viaducts, and tunnels were introduced. Ballasted track was often covered by grass to create a greener environment. Upgrading of wheel and rail profiles to new standards occurred because of the intended introduction of future light rail systems and mixed traffic.

An example of modern tram infrastructure development is the tangential regional tram Line 19 opened in 2010 between Leidschendam and the southwestern district of Delft (Tanthof). The future terminus will be in the Technical University area in the southern district of Delft. The line is partly on segregated ballasted and green track, and in the urban area, it is mostly running on a long combined (regional) bus–tram right-of-way. The line also comprises the second 1,200-m-long tram tunnel with one underground station and a large viaduct over one of the busiest highways in the Netherlands.

The development of the tram system after 2004 was strongly influenced by the introduction of RandstadRail.

TRAM TUNNEL

In the 1990s solutions were needed for the quickly increasing tram, bus, and private traffic in the city center. During the peak hours, the intersection of Grote Marktstraat and Spui was occupied each hour by trams for 55 min. Two new tram lines to the suburbs Nootdorp (2002) and Wateringseveld (1999) and the opening of the new city hall in 1995 would increase the problems. In 1991 The Hague decided to build the tram tunnel under the main shopping street (Grote Marktstraat), which had been proposed 30 years earlier as part of the semi-metro.

The 1,250-m-long tunnel (officially called Souterrain) is currently used by two tram lines and two RandstadRail lines and comprises two underground stations and an underground parking garage between the street level and the tram tunnel. One of the stations also provides underground access to shops.

As the result of a safety assessment, the tunnel is fitted with a signaling system with a simple form of train protection. The maximum speed of vehicles cannot exceed 55 km/h, and the emergency brake will be applied when a red signal is ignored.

Costs of construction were €234 million (€1 = $1.34 in February 2013). Construction started in 1996 but was not finished until 2004 because a selected technology was not appropriate under the given conditions. Water penetration occurred from leaking, and the construction needed to be reinforced.

ARTICULATED TRAMS, 1981–TODAY

Modernization and Expansion of Tram Fleet

Developments in the city and the increasingly important role of the tram system indicated that the HTM tram fleet needed to be expanded and modernized. The heavy lines were operated with PCC multiple units with conductors on the second car. Because of a new fare system and ticket validators this car became unstaffed.

Serious vandalism and incidents of fare dodging in the second cars caused HTM to consider introducing modern articulated trams with a high capacity. A technical reason was the introduction of semiconductor traction technology (DC chopper) to reduce energy consumption and reduce the number of substations in the growing tram network. Ergonomic improvements for passengers and drivers were also needed.

In the mid-1970s HTM decided to buy new articulated trams, rather than to overhaul the PCC Series 1100, which was needed after 15 to 20 years. For this purchase HTM needed approval from the Minister of Transport.

The required expansion of the capacity of the tram fleet was approximately 25%. A large expansion of stabling and maintenance facilities was needed as well. An old small depot was replaced in 1983 by a modern, new large depot with facilities for first-line maintenance.

Tram Standardization

HTM wanted to improve the tram configuration and capacity by increasing the length of tram car bodies. The result of gauge measurements was that a large part of the network was appropriate for 2.35-m-wide trams with increased distance between the truck centers. From this result, HTM made plans for a large-capacity articulated tram for the replacement of the PCC 1100.

In 1974 the Ministry of Transport established a Committee for Standardization of Tram and Metro with representatives of the ministry, public transport companies of Rotterdam, Amsterdam, The Hague, and Dutch Railways. For new trams HTM had to wait until the development of a standard tram was finished. However, standardization was difficult because of the large differences in infrastructural characteristics in these cities. The ministry finally decided to terminate the attempts to establish a tram standard, but HTM still wanted to replace the PCCs and proposed to purchase large double-articulated trams that were based on the Brussels Type 7900 tram with some ergonomic and technical improvements. Finally the ministry allowed HTM to purchase GTL8 trams, which were partly based on the Type 7900, and required that PCC trucks and other parts should be reused for cost reduction.

GTL8 Characteristics

The GTL8 (Figure 6) is a composition of existing systems and construction applied in other trams. Furthermore, parts from decommissioned PCCs such as trucks and pantographs were reused as well. Important requirements concerned ergonomic improvements, wider doors, new materials, and better corrosion protection.

The GTL8 was the first large series of rail vehicles in the Netherlands with chopper equipment. The reduction of traction energy consumption was 37% compared with a PCC multiple unit. The trams were produced by Bombardier (mechanical parts) and HOLEC (electrical equipment). In the 1980s studies were carried out for a bidirectional GTL8 and a version with a low floor middle section.

Reduction of maintenance was achieved with more modern maintenance methods and the quality of the GTL8 with electronic control, less electro-mechanical components, and other improvements. The tram fleet capacity was increased by 25%, but the maintenance effort decreased by approximately 25%.

The GTL8 is a double-articulated, single-direction tram on four PCC trucks with the following characteristics:

- Length: 28.640/29.060 m;
- Width: 2.3 m;
- Capacity: 77 seats and 108 standees (4.5/m^2);
- Weight: 37 tons; and
- Maximum speed: 65 km/h.

FIGURE 6 GTL8 tram running to Scheveningen.

GTL8 Deliveries

In 1981–1984, 100 high floor GTL8s (3000 series) were delivered. These vehicles were purchased to replace 24 PCC Series 1000 and 1200 cars for the new lines and line extensions.

In 1991–1993, the second batch of 47 vehicles (3100 series) followed; these were 40 cm longer for a larger driver's cabin. Other modifications were new swing-plug doors with over center interlock, instead of the ply doors that could be easily opened during the ride, and new communications equipment.

The old central workshop of HTM, which opened in 1905 and was built for short trams, was reconstructed in 1980 to accommodate the GTL8 trams.

RANDSTADRAIL

Introduction

By the end of the 1990s Dutch Railways wanted to transfer responsibility for the railway to Zoetermeer to other operators. HTM was interested in taking over the operation. The basis was laid for the RandstadRail light rail system that would provide other connections in The Hague and Rotterdam regions as well.

RandstadRail started with a proposal, published by HTM and RET, to Dutch Railways and regional bus operator ZWN in 1995. The plan was accepted by the government and the authorities of the Rotterdam and Haaglanden regions who started the collaboration to realize this regional light rail system.

The operation of RandstadRail was not tendered despite the open market policy aimed at competition. RET and HTM are "in-house" operators of the rail networks, including RandstadRail, with concessions for a limited period, because the cities want to keep a strong grip on the operation of the systems.

System Objectives

Objectives for the RandstadRail system were the following:

- Reduction of car traffic in the region;
- Better connections for the growing number of commuters living in the extensively urbanizing area between Rotterdam and The Hague;
- More direct connections by connecting railway lines between The Hague, Rotterdam, and Zoetermeer with the local rail systems of The Hague and Rotterdam; and
- Less transfers at Central Station to reduce space needed for passenger movements.

RandstadRail was realized by conversion of the commuter railway between The Hague and Zoetermeer and the underused railway between The Hague and Rotterdam (Figure 7). These Sprinter lines provided connections with railway stations in the cities only, but no other destinations. RandstadRail comprises three lines that are used by both tram and metro vehicles. It is a hybrid rail system combining the infrastructure of "classic" rail systems:

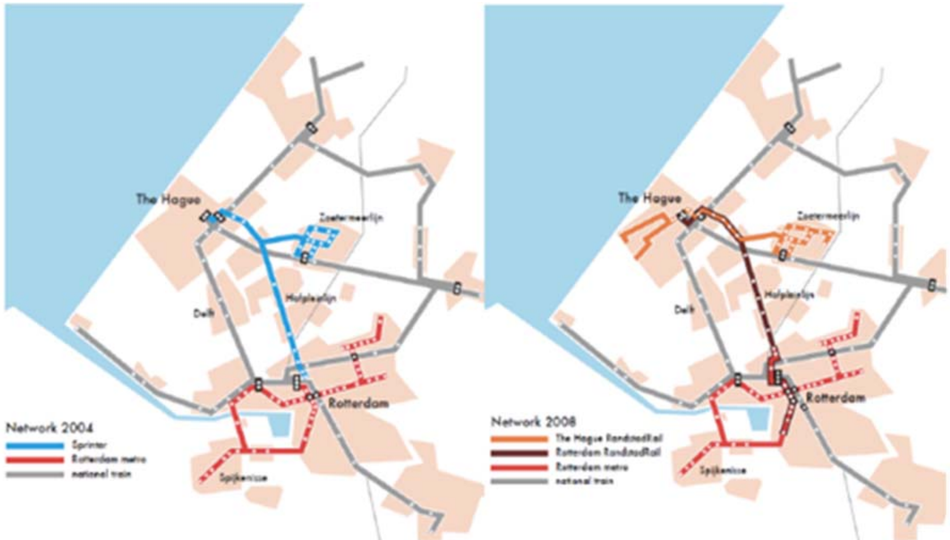


FIGURE 7 Conversion of railway lines (Sprinter) to RandstadRail.

- Lines 3 and 4 between The Hague and Zoetermeer were integrated with the tram in The Hague and operated by HTM. A viaduct with a remarkable steel structure and a station were built to connect the tram viaducts with the converted regional railway line.
- The E line operated by RET between The Hague Central Station and Rotterdam integrated with the metro and not with the tram system in Rotterdam according to the public transport policy of Rotterdam.
- Between The Hague Central Station and the suburb of Leidschenveen the three lines share tracks.

The total length of the converted railways (double track) is 44 km. The system has 23 stations and 48 stops in the cities.

Institutional Aspects, Management, and Funding

The establishment of RandstadRail required a clear political will and competent project organization. Because heavy rail, tram, and metro are subject to different legislative requirements and regulatory frameworks, planning the project was highly complex from a technical perspective. It primarily involved the transformation of existing systems, so comprehensive environmental impact assessment was not required.

Project management was shared between the two regional governments, the municipalities in the area, and RET and HTM. A project management team was established for coordination. In Rotterdam RET was responsible for the Rotterdam sections, and The Hague was responsible for the sections under its ownership.

In the beginning the project was affected by the changing relationship between local governments and the (municipal) light rail operators (in the past fully responsible for their rail systems) because of the European policy of privatization of public services, including public transport.

Planning started in 1995. Construction started in 2003, and the system was opened in 2007 after a year of initial problems and additional testing causing serious delays. The RandstadRail system opened in stages during 2006 and 2007. Some problems occurred from a strong local political pressure to finish the project in a time that was too short.

An application for funding from the national government was submitted and approved in 2002. National government was the primary source of funding, with some funding provided by local and regional governments. The final cost of the project in 2007 was €1.2 billion.

Technical and Operational Characteristics

RandstadRail Regional Trams

For the lines to Zoetermeer HTM selected the double-articulated Alstom Regio Citadis developed for mixed tram-train operation on regional railways. The vehicles are (75%) low floor to allow level boarding in cities with low platforms and can be operated as multiple units. The design speed is 100 km/h, but the maximum speed on regional RandstadRail tracks is 80 km/h.

The vehicles were designed for 600 volts of direct current (VDC) (voltage of HTM tram network) and 750 VDC (voltage of the regional sections of RandstadRail) and are fitted with wheels with a tram profile (low and fairly thin wheel flanges) because of operation in the city tram network.

The Regio Citadis has two powered trucks and two trailer trucks with the following characteristics;

- Length: 36.7 m;
- Width: 2.65 m;
- Capacity: 90 seats (including 14 folding seats) and 130 standees ($4/m^2$); and
- Weight empty: 57 tons.

RandstadRail Metro Vehicles

For the E line, RET selected the Bombardier Flexity Swift metro vehicle. The series of this bidirectional, double-articulated, high floor vehicle was part of a large order for replacement of old metros. Because of very high demand the vehicles are normally operated as multiple unit.

The metro vehicles are fitted with wheels with a heavy railway profile (high and fairly thick wheel flanges) suitable for operation in the metro network. The Flexity Swift vehicle has four powered trucks as follows:

- Length: 42,71 m;
- Width: 2.664 m;
- Capacity: 104 seats and 166 standees ($4/m^2$);
- Weight empty: 64.3 tons; and
- Maximum speed:100 km/h.

Infrastructure

Like the Rotterdam metro, RandstadRail is a 750-VDC system. The infrastructure of RandstadRail (converted railways) comprises three different configurations:

- On the 5.6-km-long shared double-track section between the tram and RandstadRail junction at station The Hague LvNOI and The Hague Leidschenveen, switches were applied with movable frogs to accommodate different wheel profiles of metro and tram. Signaling and train protection are compatible with the signaling in the tram tunnel and viaducts.
- The 20.5-m double track between The Hague Leidschenveen and Zoetermeer is suited for operation with Regio Citadis trams vehicles with tram wheels only. This portion of track has line-of-sight on surface lines, signaling, and train protection in tram tunnel and on viaducts.
- The 16.5-km double track between The Hague Leidschenveen and Rotterdam has metro characteristics and is suited for Flexity Swift metro vehicles fitted with wheels with heavy railway flanges. Signaling and train protection is compatible with the metro signaling in Rotterdam.

Current Passenger Demand

Currently the total number of passengers of both branches is more than 130,000 per day:

- The Hague-Zoetermeer Lines 3 and 4 carry 94,000 passengers per day, with a prognosis of 110,000.
- The Hague-Rotterdam (E line) has more than 37,000 passengers per day.

Lessons Learned

A number of procedural shortcomings led to five derailments in the Haaglanden region within a month of RandstadRail's operational launch.

The Dutch Safety Board carried out an independent investigation to determine exactly what had happened and what could be learned from these events so as to increase levels of safety.

Operations were suspended by the Transport and Water Management Inspectorate for almost a year and were resumed on parts of the network at the beginning of 2007.

FUTURE ROLLING STOCK

Currently 123 GTL8 trams are still available for service. For RandstadRail 72 vehicles were purchased including a surplus for future extensions. The first GTL8 trams are 34 years old but are very reliable and in good condition. Because improvement of accessibility is a hot item, the GTL8 trams need to be replaced by low floor trams. Two tram lines are now being operated with the surplus of RandstadRail vehicles. This accelerated the start of decommissioning the GTL8 trams.

The new trams should have a higher capacity because of expectations for future demand and capacity problems at a second crowded tram intersection in The Hague. By increasing capacity the number of trams that will cross the intersection can be reduced.

In 2012 the tender for a first batch of 40 trams was issued. The outcome of the tender was the selection of the Siemens Avenio tram, and the series was increased from 40 to 60 trams. Because of the width and swept path, serious adaptations of the infrastructure are necessary.

The trams have three articulations and four trucks under the four-car body sections and the following characteristics:

- Length: 35 m;
- Width: 2.55 m;
- Capacity: 64 seats + 8 folding seats and 162 standees (4/m²);
- Weight empty: 50.7 tons; and
- Maximum speed: 80 km/h.

THE HAGUE TRAM TODAY AND TOMORROW

The tram system of The Hague changed dramatically as a result of spatial developments and changing patterns of transport demand in the city and region of The Hague as part of the MRDH. The Hague decided not to establish a separate system for the heavy corridors but to adapt the tram system by upgrading and extending the network.

The network in The Hague region has a double-track length of 128 km and a 16.5-km-long connection with the Rotterdam metro network. Apart from a RandstadRail extension in Zoetermeer to a new commercial center and the tram extension to the Technical University in Delft, the network is completed.

Currently HTM operates nine city and regional tram lines and two RandstadRail lines. After the decline in the 1960s and 1970s (less than 50 million passengers per year), the current passenger demand is 85 million per year.

Because of this municipal policy the tram survived and still exists as part of the current functionally and physically integrated urban and regional rail network illustrated in Figure 5. This picture shows the current heart of the tram and RandstadRail light rail network in the Central Station area with the RandstadRail Lines 3 and 4 with tram Lines 2 and 6 from the city center (tunnel) to Zoetermeer and Leidschendam on top of the railway station and the RET E line to Rotterdam with its terminus adjacent to the platforms of the trains. At grade in front of the station are the stops of tram Lines 8, 9, 10, 16, and 17 running from the southwestern suburbs to the Scheveningen area.

Responsibility for development and planning of the tram system has shifted from The Hague and HTM to the recently established MRDH. This will guarantee a more comprehensive approach of regional mobility problems than in the past because of better cooperation between the municipalities represented in the MRDH.

The Ministry of Transport provides the MRDH with an annual broad goal-oriented grant for mobility. The MRDH is responsible for how this budget will be used. The budget includes subsidies for public transport and maintenance of the local rail systems in the region, including the HTM tram system. The MRDH is owner of the tram and light rail assets (vehicles and infrastructure) as well.

Because of the interfaces with the national railway network, Dutch Railways is still interested in regional light rail; it bought 49% of HTM shares from the City of The Hague, until 2014, 100% shareholder.

Key Directions of the Modernization of Tram Systems in Central and Eastern European Countries

GRADIMIR STEFANOVIC
GS Transport Consultancy, Ltd., United Kingdom

During the first introduction of tramways in 1870 to 1900 some 150 cities in central and eastern Europe, Russia, and Ukraine established their systems. After the end of the Second World War, in contrast with Western European cities, ridership in the central and eastern European countries (CEEC) grew by 600 to 900 rides per citizen per year.

Unfortunately, after the political changes in the CEEC in the early 1990s, cities in these countries reduced the volume of network, number of vehicles, and quality of service. To prevent further degradation of tram systems in the CEEC, the International Union for Public Transport (UITP), during its 2004 Light Rail Conference in Dresden, Germany, signed the Dresden Declaration for the Prevention of Closure and the Need for Intensive Modernization of Existing Systems. The modernization process was performed through

- Infrastructure modernization (track, power supply, and depots);
- Traffic management modernization (segregation, priority on intersections, accessibility, and integrated fares);
- Rolling stock modernization (capital refurbishment, purchase of new vehicles, and comprehensive maintenance); and
- Company restructuring and management modernization.

The ideas for modernization initiated after the Dresden conference were accepted in many cities in the CEEC.

INTRODUCTION

During the first introduction of tramways in 1870 to 1900 some 150 cities in central and eastern Europe, Russia, and Ukraine established their systems. The technological level of these systems was similar to the level of new tram systems introduced in western Europe and the United States. During that time, especially after the end of the Second World War, in contrast with western European countries, the use of public transport in the CEEC experienced continuous growth and generated an unusually large number of 600 to 900 rides per inhabitant per year. However, in the last 30 to 35 years, most of the tramway systems were not regularly maintained and were not meeting the required technical specifications. There were several main reasons for the deterioration of the condition of tramway systems in the CEEC including:

- Incoherent and unsustainable economic development with a high level of recession;

- Significant changes in land use distribution (closure of industrial zones and new commercial space developments); and
- Unstoppable and unexpected increase of individual motorization.

The Dresden Declaration, adopted by the participants at the UITP 2004 Light Rail Conference, proposed key principles for tramway renewal and modernization in the CEEC. The UITP light rail community stated the following policy recommendations:

- Tramways are not out of date and are no obstacle to transport. The many new systems established in recent years prove that existing tram systems are a solid basis for development.
- Tramways are the only surface mode that is technologically capable of offering high capacity at reasonable investments and operation costs in dense areas.
- To be sustainable and attractive to investors, cities in central and eastern Europe should not close down their systems, but should maintain and modernize them.
- Modernized trams are not only environmentally friendly, but also offer a high quality of service to customers, and provide cost-effective accessible public transport for all citizens.
- The best strategy for a city with an old tram system is to draft both political and financial transport roadmaps, which bindingly state the long-term objectives for the overall transport policy.
- For the most obsolete systems, the investment priority is in infrastructure. This should include the provision of segregated right-of-way and priorities at junctions.
- Starting a pilot line is a proven method to demonstrate undisputedly the efficiency, performance, and incremental development potential of modern light rail systems to politicians and the general public.
- Keeping lines open can only be ensured through high system efficiency. To this end, revenue and investment must be politically secured. At the same time, company management must be resolutely oriented toward efficiency and rationalization.
- The management of a public transport company should be as independent as possible. Political institutions should be restricted to providing an appropriate regulatory framework and to a supervisory role that requires the least possible interference with the daily operative work.
- In the restructuring phase at least, investments should be supported by significant public funding.
- Competition between several public transport service providers on the same route is counterproductive to efficient public transport.
- Social fares are only justified if they are properly compensated. No one company is able to provide a significant part of its services free of charge or with strong rebates.

With the support of UITP policy and local decision makers many cities intensified their efforts in creating more-effective, more-reliable, and more user-friendly tramway systems. Financing, one of the key issues, was sorted out by combining city and state support with the huge borrowing capacities offered by international financial institutions (IFIs), such as the World Bank, European Bank for Reconstruction and Development (EBRD), and European Investment Bank, as well as the European Union Cohesion Fund. After the reunification of West and East Germany, the new German government took special efforts to modernize tramway systems in the former East Germany. The result of this process was widely disseminated in other cities of the CEEC.

Today the CEEC tramway systems are transporting about 3.71 billion passengers per year [UITP tram and light rail transit (LRT)] statistics estimation) with 6,200 vehicles and a network of a total length of 2,600 km.

PLANNING OF MODERNIZATION PROCESS

Most cities followed a similar approach in defining the best strategy for modernization. These processes were performed by the following steps:

- Identifying the current condition of the tramway system,
- Identifying demands for tramway services after the modernization, and
- Identifying the key tramway performances that have to be upgraded.

For example, the city of Berlin, Germany, announced in the early 1990s a program for tramway system modernization. The components of the tram system recognized as most important are shown in Figure 1.

Within the UITP guidelines for modernization a clear strategy for modernization was suggested. It was noted that most cities followed the recommended approaches in defining affordable and sustainable strategy.

Once the key parameters were settled as fixed or within the range of incremental values (e.g., a 5-year period), a modernization strategy was adopted. In general, the modernization

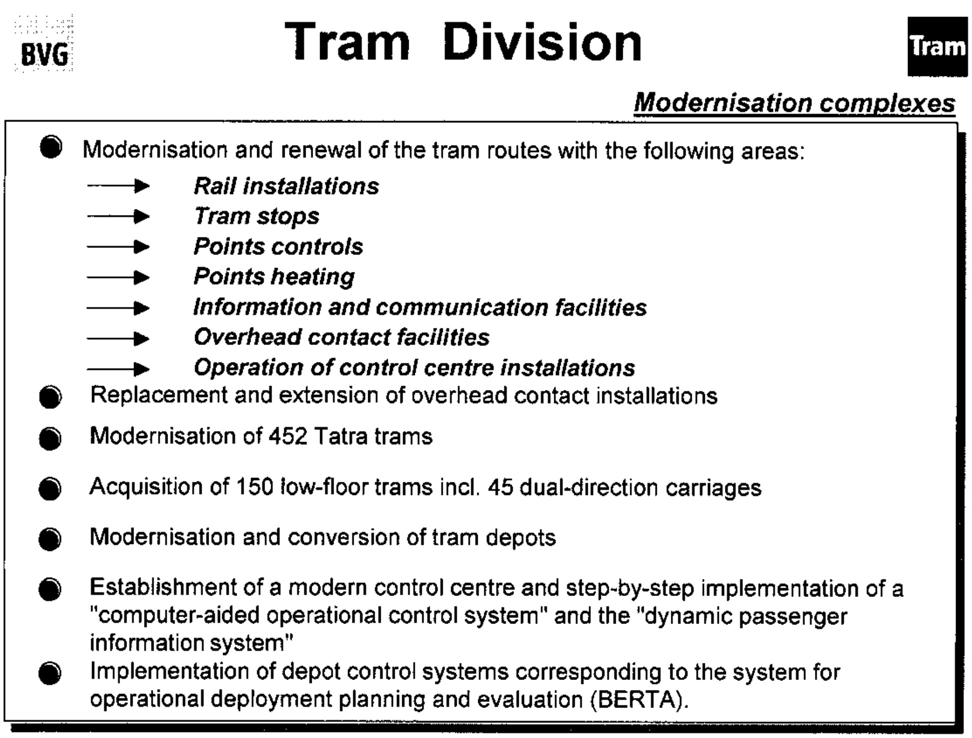


FIGURE 1 Berlin: key modernization goals in 1990 (incl. = including).

strategy is an iterative process with typical decision steps (Figure 2). Planning of the modernization process was almost always closely related with securing sustainable funding in order not to block the operation of the tramways or generate financial obligation for the operational income.

Only in a few cities in the CEEC was modernization performed on time. There was a strong dependence between the time required for modernization and overspending of the budget. In many cases prolongation was connected with an increase in construction costs. Sometimes, budgeting was not the core problem—lack of coordination or shortage of technical documentation generated significant delays. Several essential lessons were learned, such as the following:

- Funding must be linked with expected timing of modernization;
- Funding could not be a reason for delaying modernization; and
- Delays in execution should generate extra costs in financing.

Most of the cities identified very quickly the negative impact of delays, especially related to

- Providing technical documentation for track or vehicle rehabilitation;
- Providing certificates and approvals for starting activities;
- Providing appropriate time for closing traffic in the streets for track reconstruction;
- Financial inefficiency of the contractors or their subcontractors (who also had their own transition and modernization problems); and
- Poor organization in replacing or rerouting current tram services.

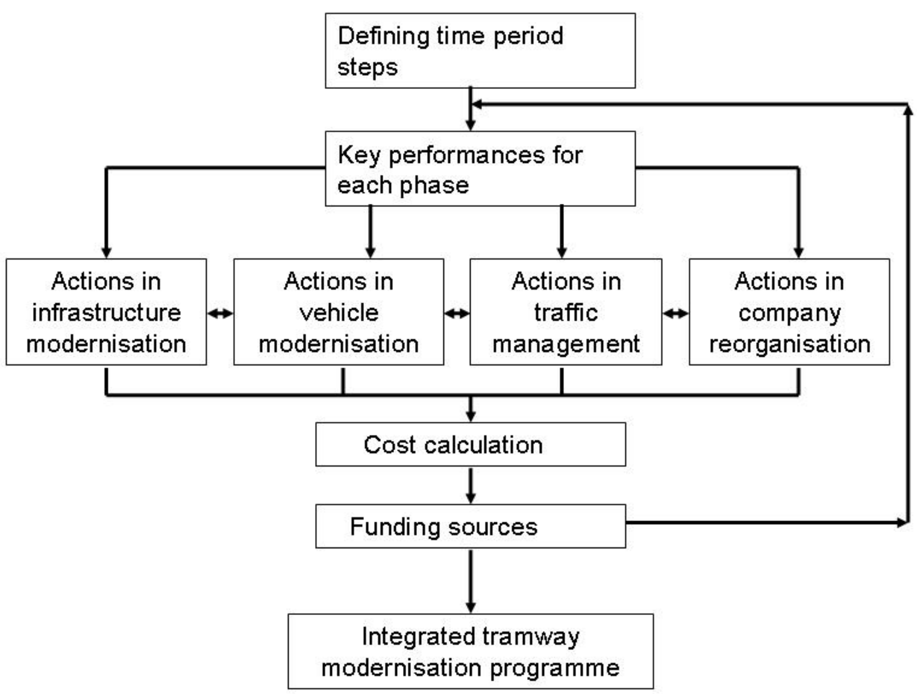


FIGURE 2 Algorithm commonly used for defining modernization strategy.

FINANCING

Financing was identified as an important element of the process. It was not simple for cities to secure financial sources in their situation of reduced volume of operation, depressed fares, and unstable cash flow, as well as a shortage of motivated personnel. Many cities considered the following sources:

- The operating company budget,
- The budget of local authorities related to traffic and transportation improvement,
- City borrowing,
- Applying to the European Union Cohesion Fund,
- Getting loans from local banks and business partners of the PT Company, and
- Taking loans from IFIs, such as the EBRD, the European Investment Bank, and the World Bank.

In the case of IFI funding the cities were obliged to follow bank policies and to demonstrate that the cost of modernization will follow the IFI goals to increase mobility in public transport, reduce pollution in the cities, and enable a modernized tramway system accessible for all categories of citizens that will cover operating costs and have secured coverage from a contract with authorities. A typical example is presented in the proposed EBRD Public Service Contract mechanism (Figure 3).

Most of the IFIs settled the general principles for loan approval. To be creditworthy, a public authority or company needs to fulfill the following three basic criteria:

- The borrower must be able to run its affairs and repay the debt (including all fees and interest), while maintaining a suitable reserve.
- All risks must have been identified and acceptable mitigation measures put in place.
- In case of default by the borrower, the financiers must be able to get their money back (i.e., suitable security must be made available).

INFRASTRUCTURE MODERNIZATION

Policy makers in the CEEC shifted their transport policies within the modernization process to provide greater priority to sustainable development and to balance the growth of motorization with the capacity to develop road infrastructure. This was achieved through the promotion of public transport, reduction of car use in urban areas, improvements to traffic management, improvements to traffic safety measures, and integration of land use and transport planning.

Public authorities and transport operators across Europe, especially in the CEEC, were under constant pressure to provide a public transport service for passengers that is of better quality and more desirable.

Table 1 shows basic information about Dresden; Warsaw, Poland; Sarajevo, Bosnia, and Herzegovina; Tallinn, Estonia; and Bucharest, Romania. These five cities vary in population and in the area served. However, they are located in the same part of Europe. Except for Sarajevo and Tallinn, the other three cities can be compared with regard to the surface railways' electric transport system (tramway and light rail vehicles–LRT), the network length of between 120 and

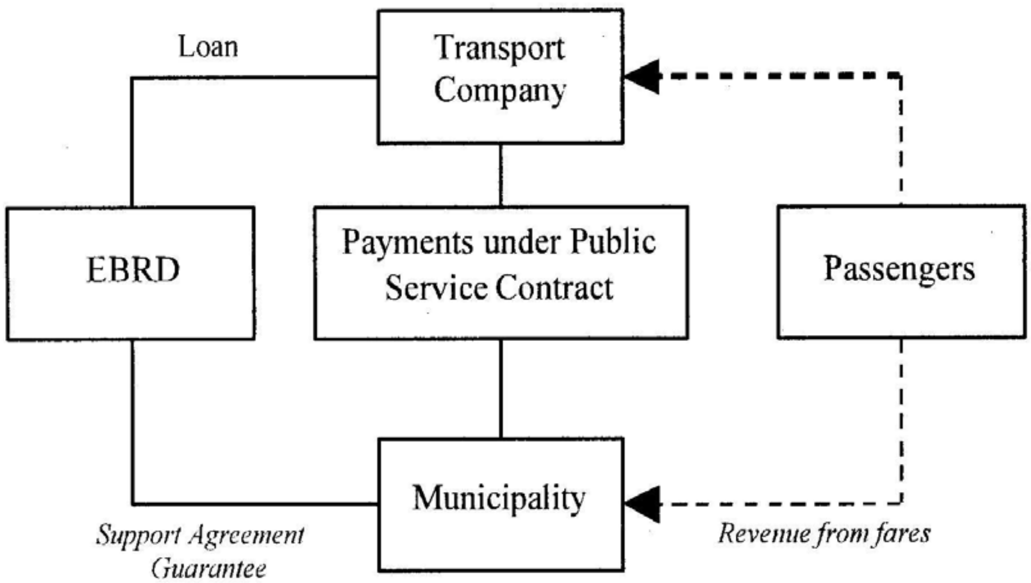


FIGURE 3 EBRD proposal for typical financing structure under a public service contract.

TABLE 1 General Information About Five Cities in the CEEC

Indicator	Bucharest	Dresden	Sarajevo	Tallinn	Warsaw
Population	2,000,000	480,000	420,000	400,000	1,700,000
Surface (km^2)	210	328	1,277	58	305
Number of routes	25	12	7	4	26
Length of network (km/double way)	143	132	12	33	121
Number of stops	593	496			
Fleet	514	309	81	95	859
Passengers transported per year (in millions)	436		56		

140 km double way, with approximately the same quantity of stops (around 500 stops), and served by a fleet that varies between 300 and 800 tramcars.

Track Condition

In Bucharest, the tram system recorded its worst performances in 1988–1989 when the general feature of tram infrastructure was an emphasized degradation caused by length of service in operation, the inadequate technical solutions that were accessible at the time of construction, and the inadequate rehabilitation program. The poor quality of tram tracks had important negative effects on the rolling stock, through an earlier wear of bogies and wheels, which meant additional money for spare parts, materials, energy, and maintenance work.

In Dresden, a system with 60 km of tram tracks, around 22% of the track network was subject to speed reduction. Almost all buildings of the DVB (Dresdner Verkehrsbetriebe), including depots, workshops, and administration offices, were in need of reconstruction and could not be operated efficiently. Only two-thirds of the vehicles were usable; the rest could not be repaired or were used as a spare part reserve. The passenger information system and the stop systems were unattractive and in no way adequate for handicapped passengers.

In Sarajevo, the worst performances of the tram system were recorded during the 1996–1999 period, except during the period of war (1992–1995). The general characteristic of tram infrastructure was in a state of heightened degradation caused by inadequate technical solutions used at the time of construction and because of the transport demand on tramlines in peak hours. The percentage of use of passenger seats on public transit going from the city center to the outer residential areas was at or below 50%, depending on the section in question.

Tram track was laid on concrete surfaces and on sleepers. Track condition was mainly very poor, which slowed down the vehicles. In certain sections the rails were worn out, and this in turn reduced transport safety. Poor track condition also affected maintenance costs. For that reason it was necessary to implement overhauling and modernization of the entire tramcar track system.

During 1998 to 2000, KJKP GRAS prepared a strategy of public transport development up to the year 2015, anticipating modernization of the tram mode and its gradual transformation into a light rail transport system. The objective of the strategy was to offer an attractive, fast, reliable, safe, economical, and comfortable surface public transport. These projects were of vital importance for the canton and the city, and consequently, they were adopted by the Cantonal Government and Assembly in 2000.

In Tallinn, 1995 was a crucial year in the renovation of tramways in the Republic of Estonia, because in the course of major repairs the tram infrastructure was switched from wooden sleepers to monolithic concrete foundations. If financial resources permit in the future, all reconstruction of tramway junctions, tram tracks, and crossroads will be switched to monolithic concrete.

The railways are divided into two types according to their installation:

- Loose installation: on wooden sleepers; and
- Fixed installation: in general, on a monolithic concrete base (renovated stretches).

But more stretches of tramways have been constructed on wooden sleepers and have been covered with asphalt for public traffic. By January 1, 2007, the overall length of tramways on wooden sleepers was 62%, and it was 38% on monolithic concrete foundations. Unfortunately, for the past 45 years, because of a shortage of financial means, new tram tracks have not been built in Tallinn. Only major renovation works have been carried out on tramways on streets while major street renovation was done.

In Warsaw, the scientific base of the upgrade plan consisted of several studies, among them the Pre-feasibility Study of the Tramway System Upgrade in Warsaw, With an Analysis of Feasibility of Bidirectional Trams Introduction on Select Routes. The study analyzed the four most-important tramway routes in the transport system of the city, which did not serve corridors that were planned to be served by the underground transport system.

Project A refers to the modernization of 12 km (the Banacha–Aleje Jerozolimskie–Gocławek route). This route transports the highest number of passengers, and the tramcar runs with an operational speed of 19.5 km/h (Figure 4).

Project B, another route in the very center of the city, with a high number of passengers and a low mean scheduled speed of around 9.3 km, along Jana Pawla II (John Paul II) Avenue, is the second route scheduled for modernization (Figure 5).

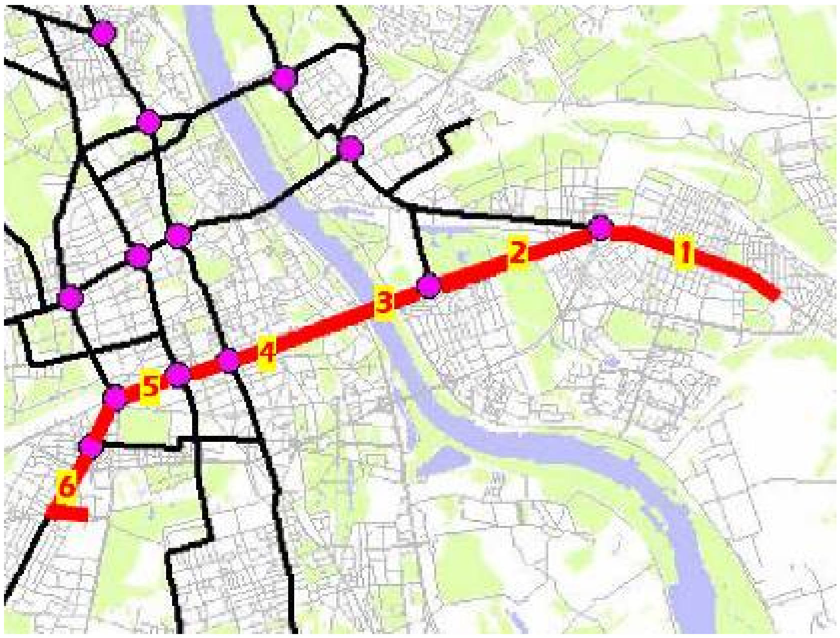


FIGURE 4 Warsaw Project A.

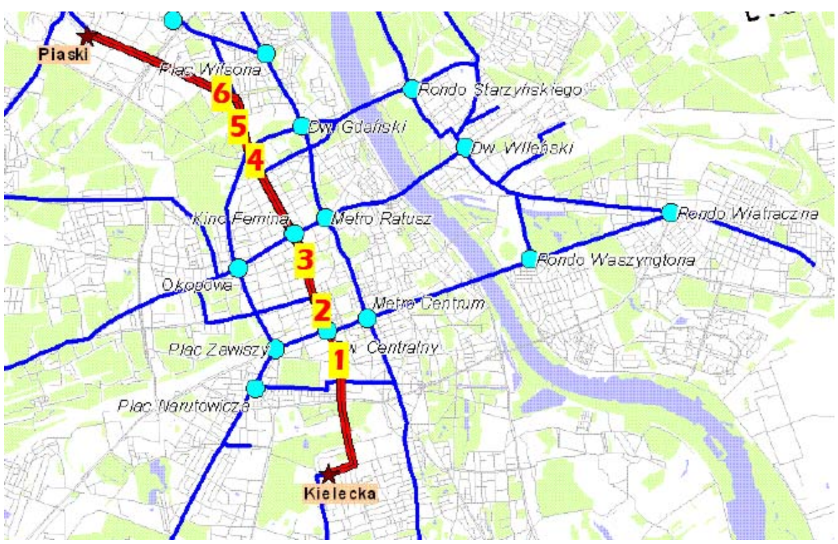


FIGURE 5 Warsaw Project B.

The third route considered for modernization, Project C, is a tramlink situated within the main east–west route, of 7.8 km, and partially separated from general traffic. The lack of separation is present within the central part of the route crossing the downtown and on a bridge over the River Vistula and is the main reason for problems existing on the route (Figure 6).

Review of the Tramway Track Structures Implemented in Modernization

Bucharest

The following track structures were used in tram modernization in Bucharest:

1. Prefabricated bearing beams solution;
2. Ballast–asphalt–concrete solution;
3. Track device solution;
4. BSP49 solution (semiprefabricated double block); and
5. Prefabricated, precompressed, reinforced-concrete sleepers' solution (ballasted track).

Dresden

In Dresden, track structures were built with cross sleepers or with so-called fixed trackway. In the versions with cross sleepers, three designs are usually used in the Dresden tramway system:

- Open (classic) permanent way on free lines and outside of residential areas.
- Closed permanent way in the case of tracks laid in streets.
- Covering of the line route for reasons of ecological acceptance. The roll grass laid to rail top level has the additional effect of reducing airborne noise emissions by up to 3 dB.

After some initial resistance, especially on the part of the city administration, the grass-covered track has greatly contributed to a wider use of lines with separate tracks.

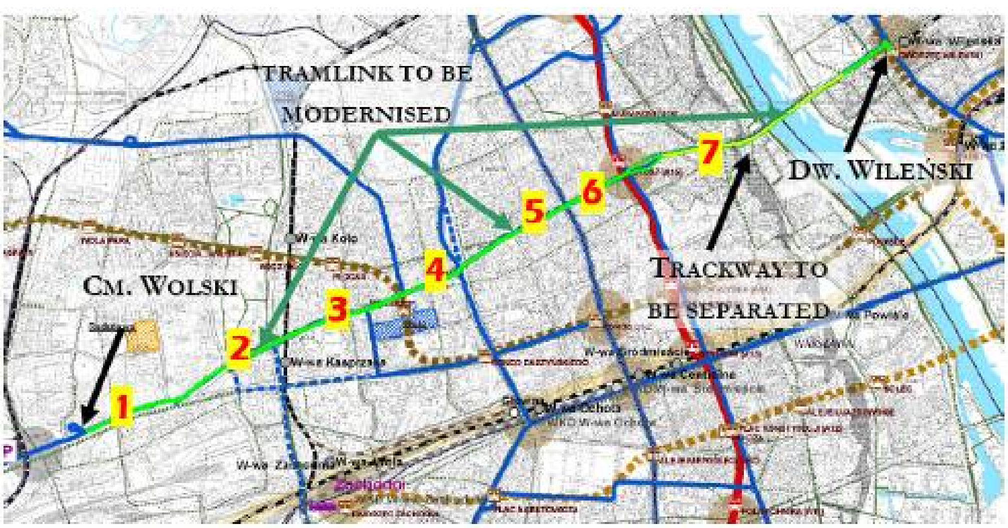


FIGURE 6 Warsaw Project C.

Three types of grass-covered track may be differentiated:

- Grass-covered track that may not be used by road vehicles;
- Grass-covered track that may be used by road vehicles in cases of emergency such as by rescue and fire-fighting vehicles, for example; and
- Special construction with track-covering slabs that may permanently be used by buses.

The fixed trackway is a type of track that was developed with the concerted support of the Dresden public transport company and has proved to be successful, especially in streets subject to an increased private transport load or a high bus density. The track gauge is maintained by two-block sleepers connected to one another with structural steel rods. After the sleeper level has been fixed, the whole sleeper area is grouted with concrete.

Two types of covering were used:

- Fixed trackway with bituminous covering, and
- Fixed trackway with paving.

The latter type is preferably used in areas with heavy bus traffic with the stone sets being fixed to one another according to a patented method using an adhesive so as to prevent them from being dislocated by the vehicle braking and starting forces.

It is an interesting fact that the fixed trackway in conjunction with the Ri53 rail section may ensure a depreciation period of the structure of about 30 years and a service life of about 15 to 17 years. The springing effect, or elasticity, which in the case of cross sleepers is achieved by the ballast, is provided here by the elastic rail supporting concept using special bearing plates that will deflect up to 0.7 mm and return the energy in a slow-rate consumption process. Thus, at speeds up to 70 km/h the airborne noise may be reduced by about 1.5 dB. Also, this design is much less susceptible to the formation of corrugations on the rails.

Budapest

Following the compilation and acceptance of preliminary studies, the progress of the program in Budapest was slowed down by working with the World Bank. Part of this was due to the structural and financial obligations required by the bank. The bank prepared its Staff Appraisal Report, on the basis of which the loan agreement was signed on October 2, 1995. The agreement defined an amount of US$67.1 million for the complete program of which US$38 million were financed by the World Bank, and US$29.1 million came from the public transport company BKV's own resources. Although the Budapest Municipality was the borrower, BKV was obliged to pay the interest and principal. This meant a considerable financial burden for the company. In total, up until 2010, some 47 km of tram tracks were reconstructed. With new tracks, Lines 4 and 6 were able to transport 70 million passengers per year (in the 1990s they transported more than 100 million per year). To understand the magnitude of this volume, these two lines transport more passengers than Philadelphia, Pennsylvania; Denver, Colorado; and Salt Lake City, Utah, combined together.

Belgrade

In 2003, the city of Belgrade decided to perform tramway and street modernization processes. According to the adopted Appraisal Report from December 2002 and a contract signed by the city of Belgrade and the EIB (June 2003), the Belgrade Reconstruction Project became an integrated project that covered the elaboration of designs, construction, and supervision of works on the following infrastructures:

- Reconstruction of tramway tracks in the total length of 33,785 m,
- Reconstruction of secondary street networks in the total length of 27,755 m, and
- Tram purchase of 30 new trams with length of 32 to 35 m.

Total costs, including items financed by the city of Belgrade, are in the range of €250 million (€1 = US$1.34 in February 2013). The track reconstruction works are still ongoing (Figure 7).

Sarajevo

Selection of the optimal infrastructure in Sarajevo is not easy because of limited funds. It was recommended to use track construction similar to that used in Budapest. The tracks, used only by tramcar and light rail vehicle (Ilidža–Marijin Dvor section), were laid on graveled surface and concrete sleepers.

In 2004, the first phase of reconstruction was successfully implemented on a 1,300-m-long section from Skenderija to Latinska ćuprija, as well as on the Otoka crossing (Figure 8).

FIGURE 7 Modernization of tramway in Belgrade.

FIGURE 8 Works in modernization of tramway tracks in Sarajevo.

In 2005, the following reconstruction works were completed:

- Track section from Latinska ćuprija to Baščaršija in a total length of 750 m;
- Track section from Marijin dvor stop to Skenderija (Hiseta Street) in total length of about 600 m, including the turnaround Skenderija; and
- Rehabilitation and reconstruction of the Nedžarići crossing.

Tallinn

The city of Tallinn used one of the most modern technologies of constructing tramway tracks, which is based on reinforced concrete prefab bearing beams. With this technology the construction of the rail track was faster in comparison with earlier methods because 6-m beams are used. The bearing beams are manufactured in special factories, and only their installation takes place on site.

There was another technology used in the construction of the Tallinn tramway tracks in major renovations that is based on monolithic concrete and is performed at the construction site. This technology in which the construction of the tramway track and the foundation of the monolithic concrete base take place at the construction site does not require a new brand of rails. This would also not require a new technology in the maintenance of the rail track and saves additional costs.

With this technology, the major renovation of Tallinn's one-way rail track in 2006 cost €0.77 million per kilometer. The rail track was built in a different place, and the cost per kilometer does not include the construction cost of the contact network (Figure 9).

FIGURE 9 Tramway tracks in Tallin.

At present, different brands of rails are in use—T62, T58, and P65—and in recent years Ri60 rails were added on straight stretches

Warsaw

The city of Warsaw decided to use several types of track structure that are based on the most appropriate geometrical and traffic conditions.

Ballastless New Berlin Streetcar Track System

The New Berlin Streetcar is popular in several German cities and is known also as the Rheda City System. The system consists of prefabricated concrete block sleepers, which are embedded in two layers of concrete and a top layer of asphalt after the rails are assembled. The rails themselves are covered with rubber straps fixed to the sides and the foot of the rail. This solution results in rails being permanently fixed to the concrete substructure and separated (through 10 mm of rubber) from the asphalt pavement of the road, which supplies a good vibration and acoustic isolation of the trackway (Figure 10).

Measurements in Berlin proved that the New Berlin Streetcar trackway, compared with an orthodox system, is very similar to the one presently used in Aleje Jerozolimskie, characterized by a vibration reduction in the 40 Hz band of up to 15 dB and a noise reduction of about 3 to 4 dB.

The trackway can be filled with asphalt, to allow for easy cleanup and the traffic of emergency vehicles or buses, or with grass or ballast.

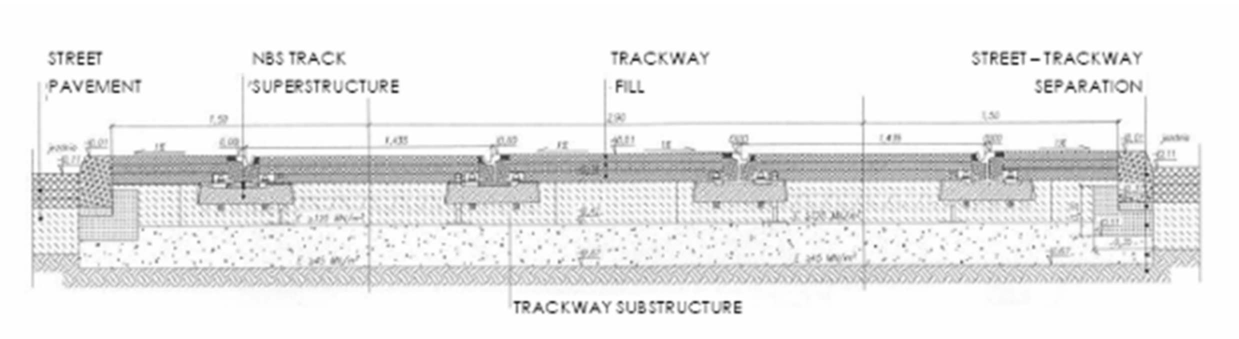


FIGURE 10 New Berlin Streetcar system.

Ballastless Embedded Rail System

The trackway in the embedded rail system consists of a rail embedded in situ in a permanently elastic resin. This is placed between concrete plates filling the trackway, on a concrete substructure plate. The system has been tested on several applications and can be characterized as having good reduction in vibration, especially in the version that is proposed in this project in which the concrete plate is placed on top of a 25-mm layer of vibro-isolating rubber. Thus, the system has two degrees of vibration absorption.

Measurements of applications indicate that the additional layer results in a 10-dB reduction in vibration in the 18- to 20-Hz band compared with the standard ballastless systems. Achieved noise reduction is up to 5 dB. The two-degree system will be used in Project A on the bridge and viaduct, and on the intersection, which are the sections most vulnerable to vibrations (Figure 11).

Calculations indicate that this structure will not be heavier than a standard ballast and sleeper trackway, which is currently being used on the bridges.

The system in Project C, an area encompassing vulnerable buildings (a hospital) very close to the route, and on a common bus and tram lane on the Slasko–Dabrowski bridge is situated within the central part of Project C. The tracks will be moved further apart because the buses have a less predictable movement corridor than does a rail-guided tramway, and it is recommended to allow for the bus drivers to safely drive with rails symmetrically placed between the wheels of the bus.

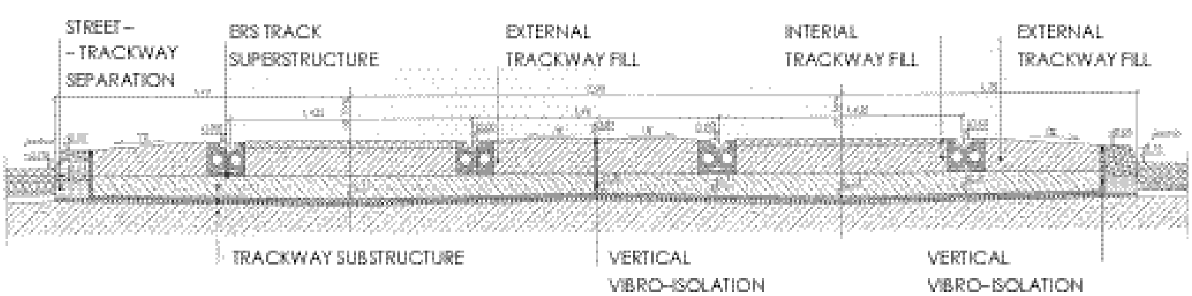


FIGURE 11 Embedded rail system.

Ballast and Sleepers' Structure

This system was proposed for use on stretches of separated trackway that do not require special vibro-isolation. This is a classic, standard trackway with no fill, except for short sections on pedestrian crossings and stops at which an asphalt fill is planned. Modernization in this case means an installation of more durable materials, such as

- A 20-cm-thick protection layer of a mix of natural and crushed stone aggregate;
- Ferrocrete sleepers with SB-type spring rail clips for a durable and stable rail support; and
- Elastomer separator under the rail to ensure good absorption of noise and vibrations.

This system has proved its efficiency after several years in use on the Warsaw tramway tracks (Figure 12).

Ballastless Trackway with Dock Rails Anchored into Ferrocrete Substructure and Asphalt Fill

This type of structure will be used mainly at junctions located on roadways. It can also be used at junctions located outside of roadways with filled areas reduced to switch areas only. Apart from track rests at which the rails are anchored, the rails will be continuously supported by a layer of permanent elastic resin (Figure 13).

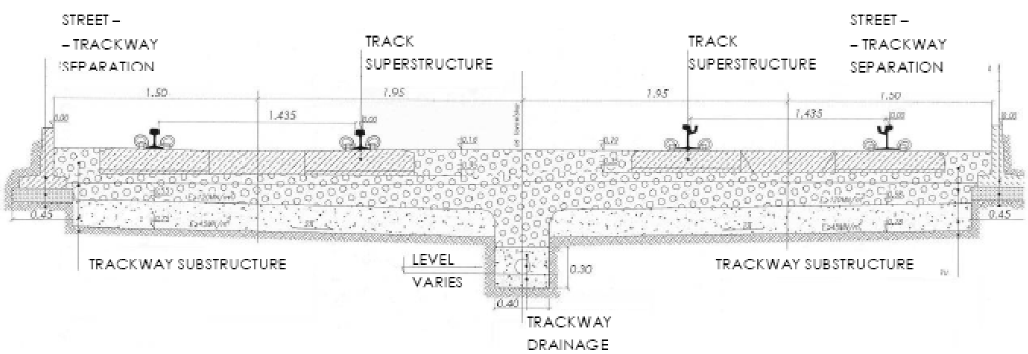


FIGURE 12 Ballast and sleepers' structure.

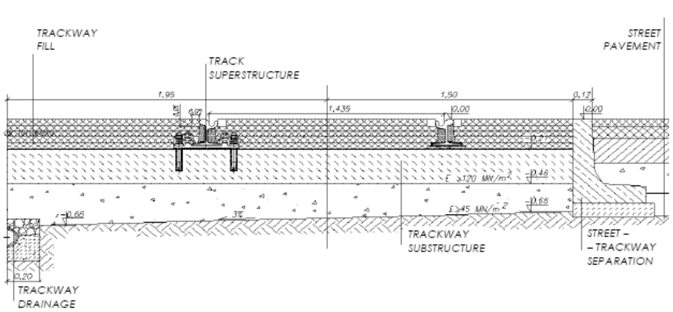


FIGURE 13 Ballastless trackway.

Review of the Power Supply System in the CEEC

Bucharest

Within the tram tracks rehabilitation works, the Bucharest PT Company performed works to modernize the power supply of the overhead network.

These rehabilitation works consisted of

- Installation of container type traction substations,
- Rehabilitation of the existing substations, and
- Replacing electric switch boxes.

Dresden

The following power supply types were implemented:

- Single contact line with messenger cable, if required, in sections with a relatively low load and in areas that are sensitive in terms of city planning. The single contact line may also be provided with bracing and with triangular suspensions in the fixed points to stabilize its position.
- The overhead contact line with catenary suspension offers a greater positional stability and may carry higher currents because of the catenary cable. It is always provided with bracing and suitable for higher speeds. Use is also made of mixed types that will not, however, be dealt with here.

Particular care was needed to take into account that the use of modern vehicles may require high currents of more than 1,000 amps, and at the same time, the voltage fed back by the return cable must be higher than the normal level plus a tolerance of 15% to allow it to reach another vehicle in the same feeder section at all (negative sequence). The use of cables with appropriate cross sections will minimize the losses of both the regular feed into the vehicles and the return feed coming up to 1,100 volts. It must be ensured that the insulation levels of the older systems and vehicles used so far are sufficient to cope with the voltage peaks encountered in such systems.

Network Control Center

The network control center, which is normally staffed around the clock, is designed depending on layout and degree of comfort to control all substations and, if provided for, also the feeding points and sectioning points. Modern computerized equipment makes it possible to use flat-panel displays so that the space required for the control center has been greatly reduced.

As a result, the operating control center and network control center could be combined in one room in the Dresden public transport company, which had a favorable effect on communication.

Sarajevo

The capacities of the electric energy supply system were adapted to increased traffic supply and changed rolling stock structure. Connections of rectifying stations with high-voltage network have to be enhanced to reduce interruptions in energy supply.

A system of remote substation control together with the introduction of a system for recuperation of braking energy may result in a 30% to 40% reduction of energy consumption because of the high level of lines overlapping.

Warsaw

According to general specifications of tramway route modernization, a power supply system should provide dependable power and full utilization of modern propulsion systems.

Because of improved dynamics, new vehicles have a greater temporary energy consumption at higher speeds, yet the overall energy balance can be reduced by the ability to recover energy (recuperation) during deceleration and a more effective propulsion system (especially during start-up). However, use of recuperation requires specific power cable solutions (shorter power sections), track interconnections, and modern power substation solutions resistant to overcharge resulting from a short-term increased power consumption. Because of the advanced technical solutions of modern tramway cars, the current should strictly adhere to the standardized range of 420 to 720 VDC.

MODERNIZATION OF TRAMWAY VEHICLES

There are several ways to ensure good technical and operational conditions of tramway vehicles, such as

- Capital refurbishment, general overhaul (without modernization);
- Vehicle modernization (of various scope and type);
- Production of an articulated tram made of two single cars;
- Use of an articulated tram with a low-floor middle section;
- Vehicle maintenance improvement;
- Secondhand purchase; and
- New vehicles procurement.

In most of the cities in the CEEC the decision depends on additional factors but primarily on the available financial budget. It is also important to decide on the production capacity to use for modernization: repair workshops of the operator, or the manufacturer of the tram vehicle, or third party subcontractor. Before making a decision, most of the cities evaluated technical, operational, and economics data, as well as criteria and expectations, such as

- Age of vehicles and their technical condition;
- Number of vehicles;
- Mileage (covered kilometers);
- Expected service life;

- Life-cycle cost; and
- Technical aspects: type of traction drive, power consumption, recuperation, spare parts availability, capacity for maintenance, and future repairs.

The final decision was based on the diversity of particular tramway types in the fleet.

Modernization of Existing Tram Vehicles

Modernization of trams makes it possible to increase quality and service life of vehicles. A very wide spectrum of modernization options were realized in CEEC cities. Before the start of modernization the following questions were raised:

1. How old are the vehicles determined for modernization?
2. How many vehicles should be modernized?
3. How long will the modernization process last?
4. What service life after the modernization should be gained?
5. Will the vehicle after modernization be further on used as a single vehicle, or should it be created as a transport unit, with low-floor section, or replace a couple of vehicles?
6. Should a low-floor part be created? And in what proportion (30% or 50%)?
7. Which parts (elements) of the vehicle should be kept (not be replaced) (e.g., traction motors, bogies, doors)?
8. Which parts should be replaced (e.g., pantograph, accelerator, doors)?
9. What is the required scope for the interior improvement (e.g., seats, windows, heating, floor, passenger information system)?
10. For how long in the future will newly used parts be available as spare parts (contract with suppliers) to avoid the Berlin case of spare parts becoming out of date?

Very often, the financial resources limited the scope of modernization.

Tatra T3 Modernization

The very frequently used tramways in CEEC cities use the T3 tram, produced by Tatra CKD in Prague, Czech Republic. This tram is very similar to the old Presidents Conference Committee car. The public transport operator in Prague has successfully achieved more than 300 modernizations of this type in its own central repair workshops.

The scope of this modernization was very large, including many mechanical, electrical, and electronic parts. It could be called total modernization and included

- General overhaul of bogies;
- General overhaul of body, including sandblasting;
- Replacement of all damaged parts;
- New cable ducts;
- Rust-free stairs;
- New painting;
- New interior, including new seats;
- Traction converter TV Progress by Cegelec;

- Static converter SMTK 6,3 by Cegelec;
- New side switchboard;
- New arrangement of driver´s control panel;
- Back running stand;
- BUSE information system;
- Dispatch system by MYPOL; and
- New door drives from BAHOZA.

The modernized trams performed on millions of kilometers after modernization. The key benefits are higher short-circuit resistance, higher humidity and impurities resistance, and maximal running comfort. Other important key benefits are the following:

- Extension of service life by 15 years;
- Electricity savings of 35%;
- Maintenance costs reduction because of extended time between periodical inspections and repairs;
- Enhanced reliability; and
- Utilization of regenerative braking.

Tatra T4D, TB4D, and B4D Modernization

Tatra tramway vehicles and trailers have been in service in Dresden since 1969–1970, with the newest since 1984. In 1992 the Tatra modernization program was started for shaping up the assembly units or the complete vehicle. During this time 40% of the rolling stock was comprehensively refurbished. Three new Tatra construction types were created with the motor car T4D MS, the modified motor car TB4D, and the trailer B4D MS.

Special modernization components are the single-arm pantograph, the static convector, the completely refurbished interior that includes the driver's cab, new windows and doors, the passenger information system, and the external design of the cars, which effects an improvement in comfort and safety, the lowering of maintenance costs, environmental compatibility, and the graphical concept. The refurbishment also contained hardware and software for the computer-aided operational control system, which included traffic light priority request, wheel flange lubrication system, strengthening of the gearbox, and electrical hydraulic braking systems for the trailers with automatic block signal ABS.

The new motor car modification TB4D results from the potential of forming train sets. This construction type is used only as a second motor car. The closed-off and air-conditioned driver's cab is not necessary. It is only equipped with an auxiliary drive console designed for shunting maneuvers.

Since the end of 1994 a thyristor control TV8 has been installed for reduction in traction energy consumption in the newly constructed motor cars T4D and TB4D replacing the resistance control unit. Apart from energy savings up to 35%, substantial improvements to the vehicle handling and the maintenance expenses reduction has been achieved.

Modernization of existing rolling stock is an advantageous method for improving tram vehicle quality and transport comfort, especially in conditions of limited financial resources. Many important effects were achieved: increase of commercial speed, reliability, service life and comfort, decrease of operational and maintenance costs, and reduction of noise. The existing vehicles in Bucharest are also professionally modernized.

Purchase of New Vehicles

The cities or operators in the CEEC who decided to purchase new vehicles based their decisions on the following factors:

- Low cost of operation with energy savings up to 25%, recuperation energy, and more-effective drive as a result of advanced technology. This is very important because consumption of energy can be 36% of total life-cycle cost.
- Less time for maintenance and more time for operation.
- Higher capacity of vehicles; this is especially important on the routes with high passenger loadings for which the critical issue is how to increase operational capacity.
- Higher passenger safety (reliable antiskid control system and high-performance brake systems).
- Environmentally friendly vehicle construction.
- Higher quality of customer service with comfortable and practical interior design, ergonomic seats, easy boarding for disabled passengers, air-conditioned passenger compartment, and so forth.
- Noise reduction up to 8 dB.
- New driver cab and ergonomic control desk, which improves driver environment.
- Closed-caption television as a security prevention against violence and vandalism.

In the beginning of the process, cities purchased low floor vehicles from manufacturers based in western Europe (e.g., Siemens, Bombardier, Alstom, Caf, and Ansaldo). In parallel with this process, the railway industry based in the Czech Republic, Poland, and Romania settled on production of low-floor vehicles. Most of the cities in the CEEC are buying new vehicles from local manufacturers, such as Skoda, Inekon, Pesa, Solaris, and Astra, which are capable of producing modern vehicles with energy preservation devices and durable main components. Some of these manufacturers are exporting their vehicles to the United States and their trams to countries in Europe.

BENEFITS OF TRAMWAY MODERNIZATION

It is not easy to calculate the direct benefits of the modernization of tramways, because a tramway line should be repaired, or modernized, or both, or even closed for further operation. A detailed analysis of the benefits of modernization was performed after the reconstruction of Line 41 in Bucharest. The results and benefits are very similar to results in other cities in the CEEC.

The estimated costs for the rehabilitation of the 110-km single-track tramway network in Bucharest are presented in Table 2. The total value of rehabilitation was €117.9 million. For Route 41, which was transformed from a tramway to LRT, the total cost, including track, platforms, terminals, and substations, was around €32 million.

TABLE 2 Review of the Costs for Tramway Modernization in Bucharest (€)

	Works	Raw Materials	Manual Labor	Plants	Total
1	Segregated track	30,309,000	3,247,000	2,526,000	36,082,000
2	Carriageable track	30,970,000	3,318,000	2,581,000	36,869,000
3	Overhead network	5,153,000	764,000	445,000	6,362,000
4	Cable network		655,000	3,949,000	4,604,000
5	Substations		2,048,000	12,288,000	14,336,000
Total					
Construction + raw materials		66,432,000	10,032,000	21,789,000	98,253,000
Designing, advices, documentation for bids					8,192,000
Utilities network					6,554,000
Contingencies					4,915,000
Total for entire rehabilitation of 110-km single way					117,914,000

Direct Benefits

The direct benefits are as follows:

1. Transport activity: The Bucharest public transport operator RATB estimates an increase of a fare collection of 10% after each section is finished as a result of the increase of transport capacity.
2. Reduction of operating costs:
   - With 80% at maintenance and repair of tram track and of electric network,
   - With 50% for repairing and maintenance of the tramcars, and
   - Because the operating speed was increased, operating staff cost was reduced by 5%.
3. Increase of transport capacity: RATB estimates an increase of 20% of commercial speed on rehabilitated sections, which means an increase of offered transport capacity.
4. Reduction of energy consumption.

At the end of the rehabilitation and modernization period, the energy consumption was reduced by 20%.

Social Benefits

This project has a significant effect on the life of an entire city with important economic effects on the local budget and improvement of life quality by

- Reduction of fuel consumption:
  - Increasing the general traffic capacity and flow and
  - Increasing public transport attractiveness, and
- Saving passenger time.

CONCLUSION

Now it is clear that the actions initiated during the UITP 2004 Light Rail Conference generated full success in preserving tramway systems in the CEEC. As a positive movement, many cities outside of the CEEC, such as Ukraine, Russian Federation, Kazakhstan, and other countries in the Commonwealth of Independent States are intensifying their efforts to modernize tramway systems. Now, the process of modernization in the CEEC is receiving more support every day from local authorities and their states as well as from the European Union Cohesion Fund. The current status of modernization in the CEEC is presented in Table 3. It shows that the process is still ongoing while keeping in mind the size of large tramway systems. For example, the total length of the tramway network in Budapest and Warsaw is equal in length to new LRT systems in 15 French cities (Table 3).

TABLE 3 Review of Current Modernization of Tramways in the CEEC

No.	Town/ City	Country	Gauge (mm)	Year Open	Length (km)	Modernization Status Level[a]		
						Tracks	Vehicles	Traffic Management
1	Berlin[b]	Germany	1,435	1865	178	5	5	5
2	Warszawa	Poland	1,435	1865	119	4	3	3
3	Budapest	Hungary	1,435	1866	156	4	3	3
4	Dresden[b]	Germany	1,450	1872	178	5	5	5
5	Leipzig[b]	Germany	1,458	1872	129.9	5	5	5
6	Gdansk	Poland	1,435	1873	50	3	3	2
7	Bucuresti	Romania	1,435	1874	155	4	3	3
8	Praha	Czech Rep.	1,435	1875	125	4	4	3
9	Wroclaw	Poland	1,435	1877	85	4	3	2
10	Szczecin	Poland	1,435	1879	40	3	3	2
11	Bydgoszcz	Poland	1,000	1880	32	3	3	2
12	Poznan	Poland	1,435	1880	64	3	3	2
13	Kraków	Poland	1,435	1882	82.8	3	3	3
14	Osijek	Croatia	1,000	1884	12	3	3	3
15	Brno	Czech Rep.	1,435	1884	75.6	3	3	3
16	Szeged	Hungary	1,435	1884	15	4	3	3
17	Sarajevo	Bosnia, Herz.	1,435	1885	24	4	3	3
18	Zagreb	Croatia	1,000	1891	51.4	3	3	3
19	Torun	Poland	1,000	1891	22	2	2	2
20	Kosice	Slovakia	1,435	1891	33.6	2	2	2
21	Beograd	Serbia	1,000	1892	50.1	3	2	3
22	Ostrava	Czech Rep.	1,435	1894	58.2	3	3	3
23	Zwickau[b]	Germany	1,000	1894	9.1	4	4	3
24	Katowice	Poland	1,435	1894	196	3	3	3
25	Elblag	Poland	1,000	1895	17.5	3	2	2
26	Bratislava	Slovakia	1,000	1895	35.3	3	3	2
27	Grudziadz	Poland	1,000	1896	12	2	2	2
28	Arad	Romania	1,000	1896	45.5	3	3	3

(*continued on next page*)

TABLE 3 (*continued*) **Review of Current Modernization of Tramways in the CEEC**

						Modernization Status Level[a]		
No.	Town/ City	Country	Gauge (mm)	Year Open	Length (km)	Tracks	Vehicles	Traffic Management
29	Liberec	Czech Rep.	1,000/1,435	1897	21	3	3	3
30	Miskolc	Hungary	1,435	1897	9	3	3	3
31	Sofia	Bulgaria	1,009	1898	110	4	3	3
32	Lódz	Poland	1,000	1898	119.6	3	3	3
33	Olomouc	Czech Rep.	1,435	1899	18.4	3	3	2
34	Plzen	Czech Rep.	1,435	1899	26	3	3	2
35	Gorzów	Poland	1,435	1899	14	2	2	2
36	Galati	Romania	1,435	1899	35	3	3	2
37	Timisoara	Romania	1,435	1899	42	2	2	2
38	Braila	Romania	1,435	1900	15	2	2	2
39	Iasi	Romania	1,000	1900	64	2	2	2
40	Oradea	Romania	1,435	1905	20	3	3	3
41	Debrecen	Hungary	1,435	1911	6	3	3	2
42	Most	Czech Rep.	1,435	1957	19	3	3	3
43	Czestochowa	Poland	1,435	1959	10.5	3	3	3
44	Sofia	Bulgaria	1,435	1987	30	3	3	3
45	Cluj-Napoca	Romania	1,435	1987	11.5	3	2	2
46	Craiova	Romania	1,435	1987	19	2	2	2
47	Ploesti	Romania	1,435	1987	18.5	2	2	2
48	Botosani	Romania	1,435	1991		2	2	2

NOTE: Herz. = Herzegovina; Rep. = Republic.
[a]1= modernization not practically started; 2 = modernization started; 3 = middle of progress; 4 = completed at about 75%, and 5 = nearly completed or fully completed.
[b] Cities in former East Germany properly modernized.

The prevention of the closure of tram systems in the CEEC and their modernization should be considered as a great success of the UITP and its professional bodies. All participants in the modernization process are proud of their work and ready to disseminate their experience to other parts of the world.

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Key Role of Sustainable Urban Mobility Plan in the Development of Light Rail Train Networks in Central and Eastern European Countries

Case Study of LRT Networks in Romania

ISTVÁN CSUZI
Oradea Transport Local SA, Romania

After a golden age in middle of last the century, traditional tram systems in Central and Eastern European countries—especially behind the "iron curtain" in the former socialist countries—experienced a period of serious decline. Starting in the 1990s, industrialized municipalities had the chance to renovate and upgrade their systems to modern light rail transit (LRT) standards. Closure of some old systems was balanced by many renewed and extended networks, where the continued use of efficient electric traction remained a priority. In defining improvement programs, transport specialists applied the principles of the European Union's (EU's) Sustainable Urban Mobility Plan (SUMP) process to offer optimal solutions correlated with real economic conditions.

This case study of the LRT networks in Romania offers detailed information about systems which have worked until today, and continue to be improved. Unfortunately, transit operators must fight for survival. Best practices adopted in some cities can be followed by the others, but support of local authorities is essential to maintain or renew tram networks. Defining the challenge for future progress of public transport are the issues of financing the operators, the infrastructural heritage of local communities, and bylaws in Romania.

INTRODUCTION

The majority of public transport (PT) journeys in the EU are undertaken via urban and suburban bus systems, which account for approximately 56% of the total. Rail-based modes make up the rest: tramways or light rail systems account for 14%, metro systems for 16%, and suburban railway makes up the remaining 14% of the total of journeys (statistics from 2012) (*1*). There is a wide variation in the corresponding shares for each mode in the Member States, with five countries having a higher share of passengers transported via urban rail modes than via buses: Germany, France, Austria, Croatia, and the Czech Republic. National contexts, such as historically strong public transport systems, as well as the economic growth combined with fast rising motorization rates may explain the high drops in demands. Countries with medium and relatively lower levels of demand for PT per urban inhabitant show very diverse trajectories in the development of demand (Figure 1).

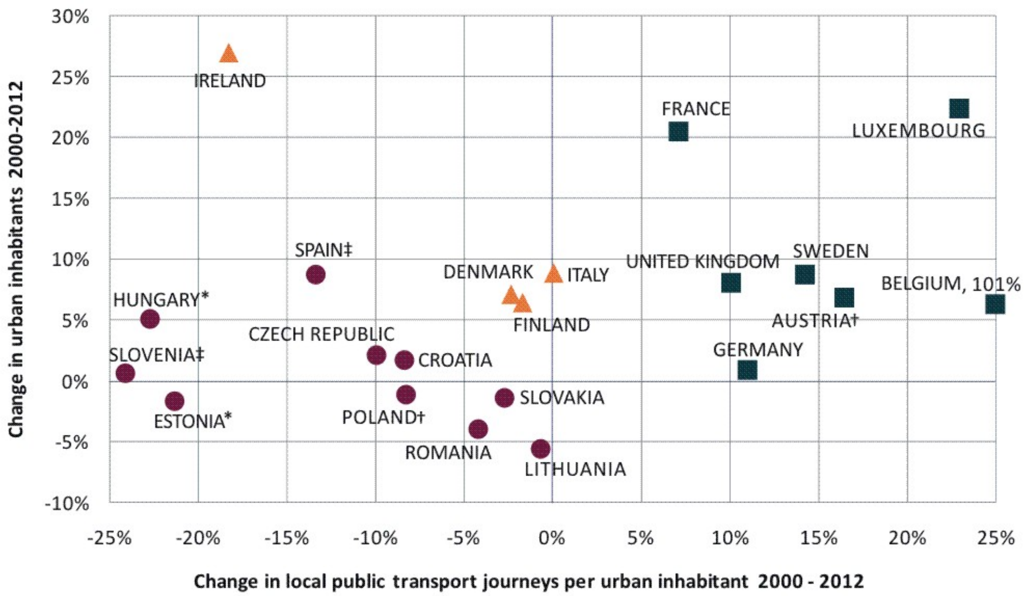


FIGURE 1 Change in local PT journeys per urban inhabitant (horizontal axis) and the change in urban population (vertical axis) in EU countries between 2000 and 2012. [Source: International Association of Public Transport (UITP), Statistics Brief 2014.]

The demand level of PT has broadly reflected the evolution of the economic situation in Europe over the last decade. However, it is likely that the dynamics of the growth which started in the middle of the decade—and have been affected by the crisis since 2009—were underpinned by some more structural evolutions, and revealed emerging changes in mobility patterns. Western European countries faced mass motorization much earlier than Central Eastern European countries (CEEC), and they simultaneously began redeveloping and improving their PT. This longer experience has paid off in recent years with increasing PT trips in urbanized areas per capita.

In the 1980s and 1990s, the concept of sustainable development emerged as an international priority and global mission.

A comprehensive definition of a sustainable transportation system is one that accomplishes the following:

- Ensures that the basic access needs of individuals and societies are met safely and in a manner which is consistent with human and ecosystem health, and with equity within and between generations and
- Is affordable, operates efficiently, offer choice of transport mode, support a vibrant economy.

Limits emissions and waste within the planet’s ability to absorb them, minimizes consumption of nonrenewable resources, limits consumption of renewable resources to the sustainable yield level, reuses and recycles its components, and minimizes the land use and the production of noise.

SUSTAINABLE URBAN MOBILITY PLAN

SUMP is a strategic document designed to contribute to meeting the European climate and energy targets. The European countries have comprehensive transport planning procedures similar to sustainable urban mobility planning. While the policy framework for urban mobility planning in some of the EU member states is quite elaborated in terms of the SUMP requirements, other member states still require amendments. In some of the EU member states, countries in CEEC in particular, planning processes are either rudimentary or simply outdated in order to sufficiently meet quality requirements which consider the needs of all transport system users. Besides the requirements for an integrated planning in many EU member states an excellent thematic planning is also common practice. For example, in Germany or Poland mandatory public transport plans have to be drawn up. Then, more and more specific cycling plans are set up in European cities. Figure 2 shows the differences of planning standards and stages among EU members (*2*).

Analyzing the PT development through SUMPs, the following can be observed: blue countries with a well-established transport policy framework (combined with a legal definition or national guidance on SUMP—U.K., Germany, France, Italy, and Norway), yellow countries which move towards an approach to sustainable mobility planning (Austria, Poland, Hungary, Spain, Portugal, Sweden, Denmark, and Finland) and violet countries which have not yet adopted mobility planning (Romania, Ireland, Slovakia, Greece, Croatia, and the Baltic states). Developing and implementing a SUMP should not be seen as an additional layer of transport planning, but should be done in compliance with and by building on present plans and processes. The concept should become part of the daily planning practice in European cities and

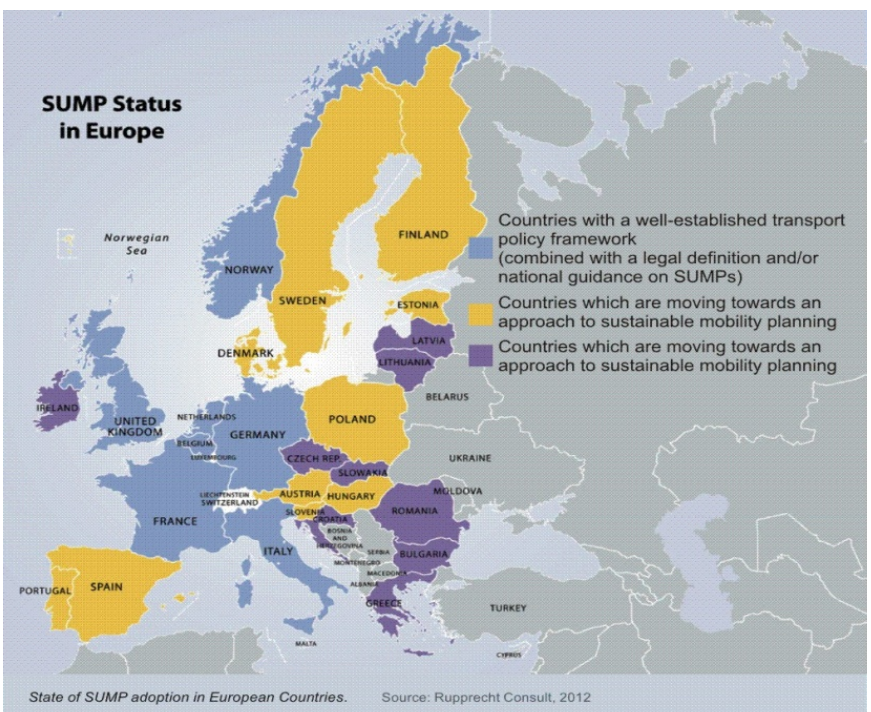


FIGURE 2 State of SUMP adoption in European countries. (Source: Rupprecht Consult, 2012.)

municipalities and should replace outdated and “traditional” planning processes, which do not have the potential to cope with the comprehensive transport planning requirements of modern times. Evaluation and monitoring activities are important steps that serve the purpose of timely identification of success or the need for readjustment of a SUMP and its instruments.

GOALS AND EFFECTS OF SUMP

For UITP the main goal of future is to double the market share of PT until 2025 (PTx2), which would make possible to stabilize urban transport greenhouse gas emissions. All strategic transport policies aim to deliver an effective, efficient, safe and accessible transport system that supports economic growth with minimum adverse environmental impact. The main questions are: how to support mobility without reducing livability and how to support economic activity without “damaging” a city? The solution recommended by an optimum of cost–impact analysis can be to choose PT by tram, implementing a competitive LRT in cities will create a win-win case.

The EU Commission proposals (EU White Papers, 2011) will dramatically reduce Europe’s dependence on imported oil and cut carbon emissions in transport up to 60% by 2050 (*3*). Therefore, an integrated mobility plan covering the catchment area of most commuting trips and defining public transport as backbone of the urban sustainable mobility system. From the integrated mobility plan, based on a medium–long-term horizon, specific plans with short–medium terms, such as a traffic plan, a PT plan, a parking plan, a freight plan, a cycling plan, and a pedestrian areas plan could be derived and monitored in their progress. There are five key principles which form the foundations of a successful SUMP implementation plan (*4*). Those are: sharing the vision, effective governance, strong links with land use planning and economic development, and long-term political and funding commitment.

TRAM SYSTEMS IN CEEC

The evolution of urban population in Europe during the last centuries has been the following: year 1800 = 12%, 1950 = 51%, and today more than 75% (*5*). From the beginning until today many tramway systems have remained operational in the CEEC, but unfortunately a lot of networks have been closed down. Trams in CEEC, especially in Eastern Europe have been strongly challenged also by the issue of aging assets and the growth in the number of private cars. Funding shortages have lead to modernization programs being postponed or left overdue. These factors (congestion and obsolescence) have resulted in a decrease of the quality of tramway services. The classical “vicious circle” is threatening—the same pattern happened before in many countries of Western Europe and in the United States after World War II—systems were neglected and finally scrapped to leave space for cars. Today the most dramatic situation is to be found in cities of Russia and the Commonwealth of Independent States (CIS), but system closures might also be possible in other CEEC cities in the near future.

Trams provide also other benefits (capacity, speed, comfort, security, economy) (*4*). Despite this positive economic, social and ecological contribution to urban life, tramways have been suffering in the last 15 to 20 years.

The reasons for the decline and loss of reliability are well identified:

- Unclear institutional and regulatory structures;
- Inadequate management framework and corporate organization;
- Insufficient political will and reform-minded support;
- Obsolescence and high maintenance costs due to lack of investments;
- Lack of segregation from individual traffic and of traffic light preemption; and
- Revenue losses due to inherited tariff rules and social fares.

In addition to funding, regulatory and management concerns also contribute to the decline of tramways. CEEC cities generally enjoy a high modal split in favor of PT and should endeavor to maintain this in order to guarantee sustainable mobility and development. The many new systems established in recent years all around the world prove that existing tram systems are a solid basis for development and long-term system efficiency, both in historic centers and pedestrian zones. In CEEC and CIS, tramways are the only surface mode that is technologically capable of offering high capacity at reasonable investments and operation costs in dense areas. Urban rail systems are the core of high-quality public transport provision. For technical, regulatory and last but not least, financial reasons, their planning and construction require long-term efforts. Rehabilitation of tram systems permits a gradual offer of better service with much less effort, money and time than new schemes.

CASE STUDY: LRT NETWORKS IN ROMANIA

The changes of last 25 years, after more than half century of communism, have transformed the behaviors of people, today's challenge being how to offer a competitive PT to satisfy the mobility needs. At the end of 1989, Romania had 15 networks, but only 11 still remain today (Bucharest, Oradea, Timişoara, Arad, Cluj, Craiova, Ploieşti, Brăila, Galaţi, Botoşani, and Iaşi); the last four cities which renounced to their tram services were Braşov, Sibiu, Constanţa, and Reşiţa in the last 15 years (Figure 3). Good news for our LRT branch: the cities of Târgu, Mureş, and Braşov have next years' PT strategy, which includes introducing or reintroducing urban railways between highly populated districts.

EU Regulation 1370/2007 gives the basic rules of PT approach for EU members. Harmonization of local law with this EU directive has been partially done; the next period will be crucial to how national lawmakers can adapt national bylaws to EU prescriptions while also respecting local needs. In Romania the organization of PT is based on Law 92/2007, which regulates local PT services. However, the regulations are not clear—there is a synchronization dysfunction between the Ministry of Transport and that of development. The number of cities with local PT services in Romania decreased from 115 at the beginning of the 1990s to 85 at the end of 2014. The infrastructure of electric transport decreased in the last 15 years by 10% for tram systems and 51% for trolleybuses, and the number of vehicles also decreased by 25%.

Trams are operated only by local PT companies, which are owned by municipalities' councils. Local authorities have the political decision about lines or routes, timesheets, and the fare system (ticket prices, revenue, and subsidies). The company management optimizes and rationalizes the services (focused on maintenance). All investments in new cars or infrastructure are decided on and financed by local governments. There are few exceptions, which means companies who have a higher level of autonomy can have their own budgets. The political and financial problems with supporting PT in Romania are caused by the discrepancies in the

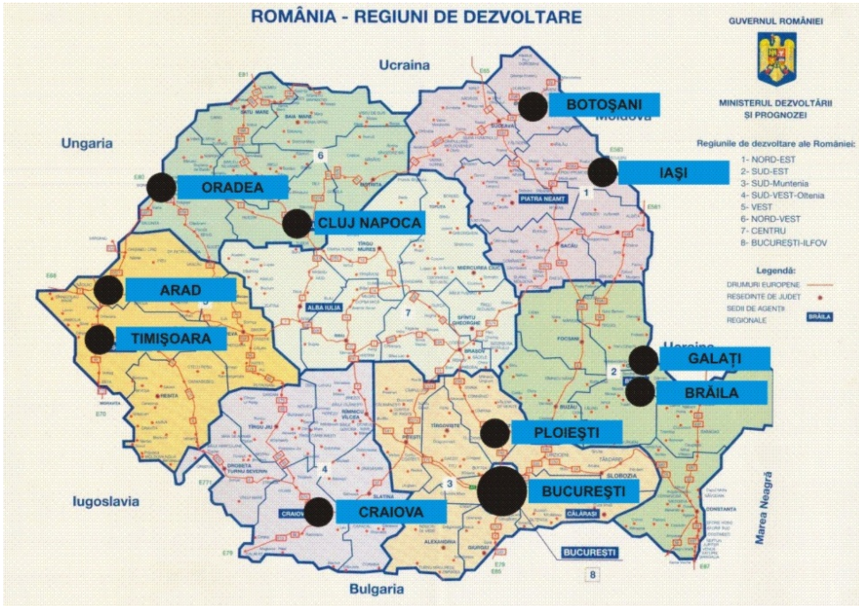


FIGURE 3 Cities with LRT networks on the map of the new defined development regions of Romania. (Source: Ministry of Development or MDRAP, Bucharest.)

expenses and revenues of Romanian PT company, vis-à-vis those of Western Europe. Romanian PT companies handle the same infrastructure and fleet renewal costs as their Western European counterparts but generate much lower revenues due to substantially lower ticket prices and median salaries.

Bucharest, the capital of Romania, has more than 2,000,000 inhabitants and it is one of the most important metropolises in southeast Europe. A recent poll presented in the publication *Urbanism* (No.10, 2011) showed that only 39% of the inhabitants use their cars during the week; of the rest of people who use PT in daily life, 83% need more pedestrian zones; 75% of the respondents said that they agreed with very severe speed limits for all vehicles in downtown.

RATB (Regia Autonoma de Transport Bucureşti) operates the surface PT (trams, trolleys, buses), which is owned by the municipality, while Metrorex, the only underground metro line operator in Romania, is owned by the Ministry of Transport. Due to this dual ownership system, the two companies sometimes face synchronization and cooperation difficulties. A typical example is the commune E-ticketing system, which after few years of joint operation was blocked by the difficulty of the financial clearing system between the two entities.

Regarding the wear of infrastructure, 2012–2013 statistics show that more than 58% of the tracks and more than 46% of the contact wires network need reconstruction (www.ratb.ro). The total installed power in substations is over 140 megawatts.

Nevertheless, there are also examples of success. Tram line 41 in Bucharest was modernized in 2002, followed by line 32 in 2003 (Figure 4). Tracks were renewed, the power supply was modernized; platforms and light rail vehicles were made accessible and equipped with real-time information; and tram priorities were implemented at some crucial junctions. A short technical presentation of Line 41: 10.2-km track length, double track, two multimodal terminals, seven power substations, and 12 stations. The entire project consisted of rebuilding the track, the platforms, and the overhead contact line systems and reinforcing the power supply systems in order to improve the commercial speed and passengers' comfort (by increasing the frequency of service). The commercial speed increased from 14 to 25 km/h, reducing travel time by 30%. The strong tram tradition made it possible to assign at least a part of the system rehabilitation to local contractors, thus keeping cost down and boosting local employment and economy, or keeping employment within the operator's structure.

Modernized trams are not only environmentally friendly, but also offer a high-quality service to customers and provide cost-effective accessible PT for all citizens (equal opportunities). Between 2000 and 2004 the locally built trams V3A were modernized for the light rail line and many prototypes were tested for the modernization of TATRA T4R trams. The fourth prototype was called BUCUR 1 (Figure 5). As a last development, BUCUR LF is the name of a new tram designed and manufactured in RATB plants. At the moment 13 BUCUR LF trams are operating in Bucharest.

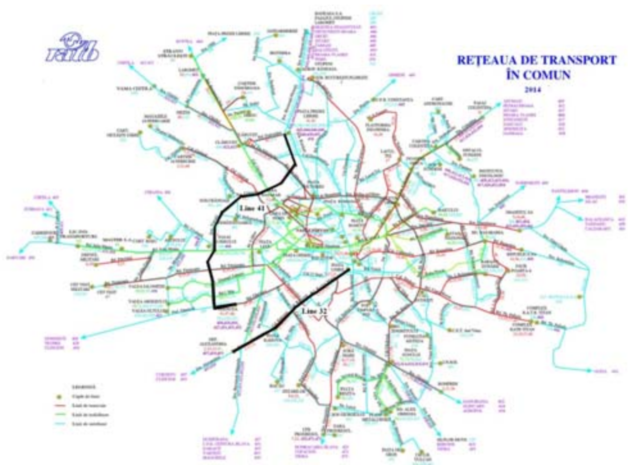


FIGURE 4 Lines 32 and 41 on RATB network map. (Source: www.ratb.ro.)

(a) **(b)**

FIGURE 5 The new tramways in Bucharest: (*a*) the prototype of BUCUR 1 and (*b*) the BUCUR LF. (Source: RATB archive.)

A lot of investments have been made during the past years, one of them being the bridge passage Basarab near the Bucharest North Railway Station. In this way, high-density districts were connected by a tram line to the most important rail and underground hub in a modern interchange.

The development strategy of RATB for the next 10 years, approved in 2010, included the elements of the next SUMP for Bucharest, which will be elaborated until March 2016 by a team of international experts. The European Bank of Reconstruction and Development (EBRD) provided financing of a project for the elaboration of the SUMPs for the eight main cities of the development regions of Romania (Figure 6).

Oradea is the first city that has prepared its own SUMP. It was elaborated in 2014 (*6*). The rolling stock renewal will be the next big challenge for operators and local decision makers. Oradea was also the city that had the first new foreign trams in Romania after many decades—10 units of Siemens ULF151, which were bought in 2009 by the municipality. The main measures proposed by the SUMP of Oradea are the extension of the existing tram lines toward commercial centers located south of the city, close to the airport, while also connecting the university to the city center. Since the local funds are insufficient to acquire new trams, and the possibilities to access reimbursable funds (EU or others) are very faint, the only realistic chance is to modernize the existing fleet (traction system by asynchronous motors with brake energy recovery; heating, ventilation and air conditioning; facelift, etc.). All these can be done through the results of a completed EU project, the Mechatronica Laboratory for PT safety, owned by OTL SA (the local PT operator in Oradea).

The red line shows the current network of tramways in Oradea and the blue one represents the proposed extension of track lines in the near future, which was also included in the SUMP and the General Development Strategy of Oradea. After opening in 1906, there were 19 km of tracks. The maximum track length was reached in the "golden age" of trams in Oradea, that is, at the end of the 1950s, when the 11 passenger lines and the industrial connections

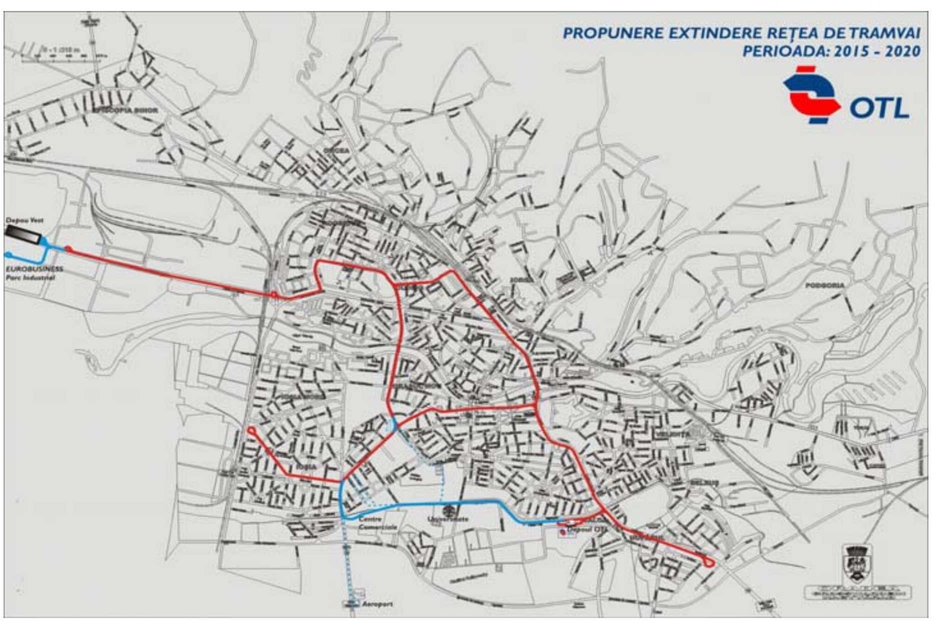


FIGURE 6 Oradea–SUMP: tram extension map. (source: OTL SA archive)

between factories increased up to 79 km (*7*). After the 1960s, the political decision was to promote bus systems so trams were kept only to connect the southern and western districts of the city while the rest of Oradea was sentenced for bus lines.

The authorities argued that it was very expensive to maintain the tracks. During the 1970s and 1980s fuel was more affordable, the technologies used to power trams were not very efficient, the tram systems seemed less flexible than the bus ones, and in the short term, the cost analysis showed an advantage for buses. That was the reason for stopping the trams in the first decades of the reconstruction of democracy in other cities of Romania as well: Constanţa, Braşov, Sibiu, and Reşiţa. These cities gave up their tram services claiming that the maintenance and repair costs of tracks and vehicles would be far too high. The decisions came at the end of a long process; for many years neither money nor time was spent to renew the tracks. Before 1989, the vehicles were almost exclusively Romanian tram cars (with a questionable quality). The second-hand trams imported after 1990 did not prove to be the best choice for cost optimization. Taking out the trams from the streets was also supported by citizens, most of whome saw that as an approval to have their own cars and to use them everywhere and at any time. Only during the last 10 years have the authorities, both at national and local levels, begun to understand that the environmental criteria must be a maximum priority, that traffic congestion can cause a high degradation of life quality in cities, and that placing PT at the first priority, especially the electric PT, will be the main challenge for everybody in the future.

The local authorities, as owners of PT companies, together with tramway operators, try to do their best. Some of them have the chance to develop their systems, others have possibilities for maintaining the present situation but, unfortunately, some of them fight to survive, and without real support, they will have to stop the services in a few years.

Developing the LRT infrastructure of all networks was a real challenge for transport companies and local authorities. Table 1 shows how some of them managed to access financing for investments, especially the municipalities. Bucharest, Oradea, Cluj, Iaşi, Timişoara, and Ploieşti are the best practice examples, as these cities by accessing EU funds, reimbursable loans from the EBRD or the EIB (European Investment Bank) have managed to keep maintenance and development of their systems at acceptable levels. To help you get an idea of the level of investments in some cities, here is the example of Cluj, where as much as €27 million were spent on the renewal of the LRT, from which amount almost €19 million were used for infrastructure (track lines, tram stops, real-time passenger info system, e-ticketing system, automatic ticket vending machines, and others). The rest of the money was spent on tram vehicles (four new PESA trams, made in Poland), as well as on more than 100 new buses. The ratio of trams to buses shows the local PT policies, how the local administration tries to solve the problem of urban mobility: buses are cheaper for the short term, but a life-cycle cost management analysis could show that a long-term strategy would tip the balance in favor of trams. Politicians sometime do not think about the future, focusing on one tenure only became “dangerous.” An example of tram modernization is that of Timişoara, where tram ARMONIA TM is part of a 30-tram renewal project in a total amount of €15 million (the first prototypes cost €486,000).

The figures for Oradea show that approximately 70% of the PT passengers use the trams and the rest use buses (*5*) (Table 2). Thus, developing the tram systems has become essential and the biggest challenge of the next years. In 2007, the Municipality Oradea got a loan from the EIB Luxemburg and Dexia Bank Brussels for new vehicles, in amount of €33,000,000 for 10 trams

TABLE 1 Romanian Municipalities in 2015 Where Operate Tramways (*10*)

City	Start	Network (km)	Trams	General Observations
Bucharest	1894	134,0	481	Partly reconstructed, other projects in progress, 13 new trams built in own factory (BUCUR LF between 2011–2015), V3A-I.T.Bucuresti, TATRA
Oradea	1906	39,86	68	Renew in progress (80% finished), 10 new trams SIEMENS ULF151 (2009), TATRA secondhand
Timişoara	1899	90,7	93	Reconstruction under analysis, tram modernization in progress: 2 pc ARMONIA TM (2015), secondhand
Arad	1913	130,8	120	Reconstruction ended in 2014, 6 new trams SIEMENS-ASTRA IMPERIO (2014), TATRA secondhand
Cluj	1987	23,7	37	Ongoing reconstruction of track, 4 new trams PESA SWING (2013), TATRA secondhand trams
Braila	1900	49,15	29	"Fight to survive," secondhand trams
Galaţi	1900	34,85	57	"Fight to survive," secondhand trams
Iaşi	1900	98,5	141	Reconstruction started 5 years ago, the end of 2016? TATRA secondhand trams
Botoşani	1991	15,8	31	"Fight to survive," secondhand trams
Craiova	1987	18,4	27	Reconstruction projects started, new trams—2017?
Ploieşti	1987	20,6	33	Under reconstruction, reopen in 2016, new trams?

and 20 buses. In the last 5 years OTL SA introduced a GPS-based performance fleet management and an online passenger information system in 2009 (€700,000); a radio frequency identification (RFID) card-based e-ticketing system (€400,000) in 2013; a great number of maintenance equipment was purchased through the Mechatronica Laboratory (by EU project funding of €4,000,000) in 2014; and the e-ticketing system was extended in the metropolitan area (by EU project funding of €250,000) in 2015. The integrated RFID ticketing system works on the same price—the OTL monthly ticket is valid for all vehicles without any limitation (municipal: 70 RON ~ US$18.5/month; metropolitan: 110 RON ~ US$28.5). In Oradea (~200,000 inhabitants) approximately 25,000 commuters arrive daily from the neighboring towns and villages. OTL SA has built three interchange intermodal bus stations (Nufărul, Decebal, and CFR, or Romanian Railways). Inside Oradea OTL there are five tram lines and 17 bus lines. In the metropolitan area there are five bus lines and one international line (which crosses the border to the first city in Hungary with six bus service daily).

Figure 7 shows some relevant pictures from Romanian tramways in traffic.

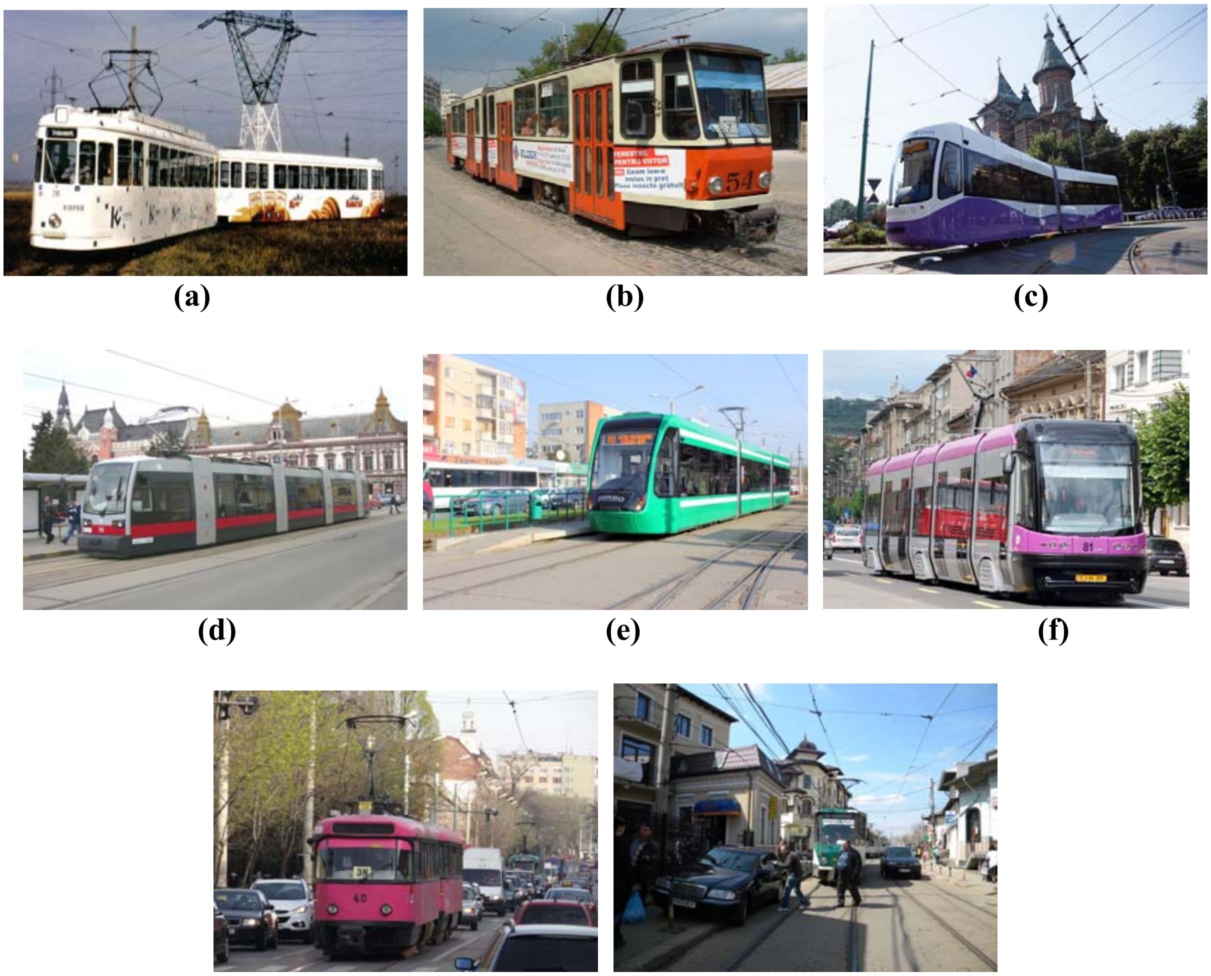
CONCLUSIONS

With more than one-century-old tramway systems in Romania preserving the current conditions is not easy job. SUMP may be the main instrument to sustain the survival of the few networks, to help their renewal, as well as the revival of other LRT systems. In order to have compatible, sustainable, high-quality tram services in cities and regional capitals, politicians must provide

TABLE 2 Past 12 Years of LRT Infrastructure Investments in Oradea

Year	Location	Description of Investment	Length of Track Lines Involved	Value of Investment (approx. Euros)	Financed by
2003–2006	Republicii and Decebal Boulevard (partially)	Rebuilt infrastructure and track lines (partially "ORTEC" and encased concrete)	9,700 m	5,500,000	PPP (private companies credit the municipality for 8 years)
2005	Between railway station and Olosig intersection	Change the track lines	1,700 m	320,000	OTL
2005–2007	Magheru and Cantemir Boulevard	Change infrastructure (concrete sleepers system)	6,700 m	1,100,000	Municipality
2008	85 tram station in Oradea	Tram platform adaptation for Low Floor trams (Siemens ULF 151- low ground clearance = 17 cm!)	85 stations	900,000	Municipality
2009	Aradului and Lipovei street	Renew track lines	1,000 m	250,000	OTL
2010	Civic Center–Cantemir–Cele 3 Crisuri str, incl. Dacia Bridge	Redesign and built new tram intersection (EDILON SEDRA)	1,100 m	2,100,000	60% Munic. 40% OTL
2011	"Sinteza" area	Change track lines	250 m	100,000	OTL
2012	Junction (loop) Pod CFR	Change track lines and 2 switches	150 m	75,000	OTL
2013	Decebal and Republicii (partially)	Binding and refurbishing track lines	1,600 m	30,000	OTL
2014	Intersection of Dacia Blvd. and Transylvania Blvd.	Renew track lines	300 m	100,000	OTL
2015	Unirii Square and Independentei St.	Renew track lines (EDILON SEDRA)	1,000 m	1,100,000	Municipality

their help and must give more support to the development of PT. The last programming period of EU funding has not been well used by the Romanian government. In the same time, the other former socialist countries have accessed hundreds of millions of Euros (nonreimbursable funds) for the renewal and extension of LRT systems and purchase of new tram cars. Examples of best practices can be seen in Poland (Warsaw, Krakow, Poznan) or Hungary (Budapest, Debrecen, Miskolc, Szeged). All of them have very good PT strategies. They have all applied SUMP



(a) (b) (c)

(d) (e) (f)

(g) (h)

FIGURE 7 Old and new type of trams in Romania and behavior obstacle: (*a*) Braila–Siemens (1959); (*b*) Galati–Tatra KT4 (1978); (*c*) Timisoara–Armonia (2015); (*d*) Oradea–Siemens ULF (2009); (*e*) Arad–Astra Imperio (2015); (*f*) Cluj–Pesa Swing (2013); (*g*) Oradea–Trams in congestion (2014); and (*h*) Ploiesti–Tram blocked by car (2012). (Source: OTL SA archive.)

measures and they update the stage of implementation yearly. The present EU funding period (2014–2020) give cause for optimism among Romanian tram operators, as all of them will be included in a possible renewal program, each one with a nonreimbursable funding amount of €20 million. The rest of the funds should be provided by local authorities. Although during the last period the Romanian governments have neglected the tramways as a result of the lobby efforts of our branch, they are trying now to correct the situation of electric PT.

The summer of 2016 is the deadline for all local administrations to approve SUMPs included in the transport master plans or General Urban Development Plans of the municipalities that benefited from the financial support of EBRD and the Ministry of Regional Development and Public Administration. The Regional Operational Program helps to prioritize public transport, recognizes the importance of PT as it is done in the notice 2009/C175/08 of the Economic and Social Committee of the EU, which states that PT is the fourth most important social inclusion factor (together with the right to housing, to work, and to equality of chances).

In order to access EU funds, a few documents should be prepared. The first and most important is the SUMP, which has to be approved by the local councils. A very good approach to the projects as components of integrated development plans is excellent technical projects, which use the newest technologies, and the financial contribution of the applicant (between 5% to 50%, depending on the impacts and the type of the project). The general conclusion can be only one: dream free and have the courage to put your dreams in practice, fight smartly for the future of trams, perseverance will bring results.

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Appendixes

AMERICAN PUBLIC TRANSPORTATION ASSOCIATION

13th National Light Rail & Streetcar Conference

"Transforming Urban Areas"

November 15 – 17, 2015
Hyatt Regency Hotel
Minneapolis, MN

Welcome to the 13th National Light Rail & Streetcar Conference. Since the 1980s, light rail and streetcars have led a renaissance in the transit industry, which is now experiencing its highest ridership in six decades. This conference will show decision-makers how investments in light rail and streetcars can strengthen the entire transit network, contribute to regional mobility, and integrate successfully into the built environment. Exploring ways to plan, design, construct, maintain, and operate light rail and streetcar systems, sessions will showcase the positive results seen in metropolitan areas that have embraced light rail and streetcars.

The host for this conference is Metro Transit, serving the Minneapolis/St. Paul areas, and an innovative leader in public transportation. A decade after its first light rail line between Downtown Minneapolis and the Mall of America, Metro Transit opened a second line linking Minneapolis and St. Paul last year and is planning additional extensions. Metro Transit is proud to share with you how its integrated light rail transit system is connecting the region together and building a more prosperous and sustainable Twin Cities.

Metro Transit

Serving the Minneapolis / St. Paul Area

Metro Transit is the primary provider of public transit services in the Twin Cities. It is a division of the Metropolitan Council, the region's metropolitan planning organization. Metro Transit's service area covers 900 plus square miles and more than 90 municipalities. In 2014, Metro Transit provided 84.5 million bus, light rail, and commuter rail rides, the highest ridership since 1981. In addition, Metro Transit and the Metropolitan Council offer resources for biking, carpooling, and vanpooling, and partner with local bike and car sharing services to promote a variety of transportation choices to residents and visitors of the region.

Metro Transit operates a fleet of 86 light rail vehicles, 900 buses – including 132 hybrid-electric buses – 18 commuter rail cars and six locomotives. The region's first light rail line, the METRO Blue Line, opened in 2004. The METRO Green Line opened in June 2014. These lines share stations in downtown Minneapolis and together stretch approximately 21.3 miles. Ridership on the Green Line has surpassed expectations during its first year of operation, with average weekday ridership exceeding 40,000 rides on several occasions. Significant numbers of riders are using the three METRO lines, including the Red Line BRT, to attend sporting events, travel to and from the Minneapolis-St. Paul International Airport, the University of Minnesota or one of the many other colleges and universities, in addition to commuting between major employment centers.

Metro Transit's five-year vision, Toward 2020, includes expanding the core bus system and implementing arterial BRT service on several major transportation corridors. The region's first arterial BRT line, the A Line, will connect the Blue and Green lines when it opens in early 2016. Extensions of the METRO Blue and Green lines will add another 30 miles of light rail to the METRO system. In addition, new highway BRT lines are planned on I-35W south of downtown Minneapolis and along I-94 east from downtown St. Paul.

SAINT PAUL

The Most Livable City in America

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Dear Colleagues,

Welcome to the 13th annual APTA/TRB National Light Rail and Streetcar Conference. Minneapolis and Saint Paul are honored to host what promises to be an exciting conversation about transit's role in shaping the world's great cities.

We are especially proud of the newly opened Green Line that links our two downtowns with the University of Minnesota and dozens of neighborhoods along the way. After just 16 months of operation, the Green Line is exceeding ridership expectations and surprising all of us with how quickly it has integrated itself into the fabric of our cities.

In addition, transit projects are currently in various stages of planning on other key corridors like Nicollet/Central Avenues in Minneapolis and West 7th/ East 7th in Saint Paul.

So, while you're here, hop on a train and find your way to one of our many fine restaurants, shopping districts or other historic, cultural and scenic attractions.

Best wishes for a wonderful conference.

Sincerely,

Mayor Christopher B. Coleman
City of Saint Paul

Mayor Betsy Hodges
City of Minneapolis

November 2015

On behalf of all those who work at Metro Transit, I'd like to welcome you to the 13th National Light Rail & Streetcar Conference. It's our honor to serve as the host transit agency for this exciting gathering.

The Twin Cities is the proud home of a robust multi-model transit system that includes not just light rail but buses, Bus Rapid Transit and Commuter Rail. I hope you will have the opportunity to experience our system first hand during your stay.

Minnesota was introduced to light rail more than a decade ago when we opened the METRO Blue Line connecting downtown Minneapolis, the Minneapolis-St. Paul International Airport and the Mall of America. Since then, there have been more than 100 million rides on this light rail line – far exceeding initial expectations.

In 2014, we introduced the METRO Green Line, which meets the Blue Line in downtown Minneapolis and continues east to the University of Minnesota, the state Capitol and downtown St. Paul. Almost overnight, the Green Line brought our communities closer together and created a buzz that continues to build throughout the corridor.

Building on these successes, we look forward to extending each of these light rail lines in the years ahead. We also have ambitious plans to expand and improve bus service, support transit-oriented development, deepen our commitment to sustainability and be an equity leader.

I hope you enjoy your time in the Twin Cities and leave our community feeling inspired to continue doing great work. Thank you for visiting and enjoy the conference.

Best wishes for a wonderful conference.

Warmest Regards

Brian J. Lamb
General Manager, Metro Transit
Minneapolis. MN

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Moderators/Speakers Room

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8 – 9:30 a.m.
Lake Minnetonka
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APTA Streetcar Subcommittee Meeting

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12 – 4 p.m.
(on your own)

Tour of Minneapolis Heritage Trolley Museum

The Minneapolis Streetcar Museum operates the Como-Harriet Streetcar Line, which includes a mile of the original line that was abandoned in 1954. The streetcars are 100+ years old and were built by Twin City Rapid Transit. The streetcar fare is $2.

By Bus: From the Hyatt Regency, walk north one block to 12th Street. Turn left on 12th Street and walk four blocks to Hennepin Avenue. Catch any Route 6 bus headed south (to your left), which run every 15 minutes. The fare is $1.75. The trip takes about 20 minutes. Get off at the first stop next to Lake Calhoun. The streetcar stops across the street, and runs about every 20 minutes.

By Car: LaSalle Avenue runs behind the Hyatt Regency. Take LaSalle to 36th Street. Turn right on 36th to Lake Calhoun. Turn left at Lake Calhoun and you'll see the trolley tracks. You can park there or continue to William Berry Road and turn left. Follow Berry Road to Lake Harriet and look for the depot to the right of the bandshell and refectory.

5:30 – 7:30 p.m.
Great Lakes A & B
Fourth Floor

Opening Welcome Reception

Enjoy the hospitality of our opening reception. Meet old and new friends and network with your transit industry peers while examining the displays in the showcase. There's no better way to keep up with what's happening than the informal, relaxed ambiance of the opening reception – the official conference kickoff.

5:30 – 7:30 p.m.
Great Lakes A & B
Fourth Floor

Light Rail & Streetcar Products and Services Showcase

Back by popular demand! The manufacturers, suppliers, and consultants to the light rail and streetcar industry have come together to display their products and showcase their services. We are sure you'll enjoy walking the aisles and speaking with representatives of these companies to find out more about how they can help solve your particular problems or provide just what you need. As we envision an influx of new funding and new projects, our vendors will play a crucial role in our vision to expand light rail and streetcar service. Stop by and learn what new technologies are on the horizon. And, you don't have to leave to attend the opening reception – it's in the same room.

Thank You To Our Exhibitors

- **ALSTOM Transportation** Table 25
- **Altro Transflor** Table 9
- **American Traction Systems** Table 23
- **Apollo Video Technology** Table 1
- **BAE Batteries USA** Table 20
- **Bode North America, Inc.** Table 14
- **Brookville Equipment Corp** Table 18
- **CAF USA, Inc.** Table 21
- **CJ Geo** Table 16
- **Daktronics** Table 13
- **Digi International** Table 12
- **FAAC Incorporated** Table 19
- **Irwin Transportation Products** Table 4
- **KLD Labs, Inc.** Table 24
- **Los Angeles County Metropolitan Transportation Authority** Table 2
- **Penn Machine Co.** Table 10

- **Protran Technology** Table 15
- **Rugged Coatings** Table 17
- **Siemens Industry, Inc.** Table 6
- **Sportworks Northwest Inc.** Table 7
- **TDG Transit Design Group** Table 8
- **Thales Transport & Security, Inc.** Table 5
- **The Reinforced Earth Company** Table 3
- **Vossloh North America** Table 22
- **Zen Industrial Services LLC** Table 11

Monday, November 16

7 a.m. – 5 p.m.
Great Lakes Promenade
Fourth Floor

Registration Desk
Host/TRB/TCRP Information Desks

Cedar Lake
Fourth Floor

Moderators/Speakers Room

7 – 7:30 a.m.
Great Lakes Promenade
Fourth Floor

Continental Breakfast

Breakfast sponsored by Kimley-Horn and Associates, Inc.

Kimley»Horn

7:45 – 9 a.m.
Great Lakes C
Fourth Floor

OPENING GENERAL SESSION

This is where it all starts for the joint conference. We have included many perspectives on the light rail and streetcar industry around the country. Hear from the Mayor of Minneapolis about her vision for rail transit in the region. Also hear about innovative future projects as seen by leaders at APTA and TRB, and the status of light rail projects in North America.

Presiding
John D. Wilkins, Chair, 13th National Light Rail & Streetcar Conference Planning Committee, and former Director of Capital Planning and Programing, New Jersey Transit Corporation, Gillette, NJ

Sponsor Recognition
Michael S. Townes, Vice Chair, APTA Business Member Government Affairs Committee, and Senior Vice President/National Transit Market Sector Leader, HNTB Corporation, Hampton, VA

Status of North American LRT & Streetcar Systems John Schumann, Senior Transportation Consultant-On Call, LTK Engineering Services, Portland, OR

Ted Rosenbaum, Senior Consultant, LTK Engineering Services, San Francisco, CA

Welcomes
Peter McLaughlin, Hennepin County Commissioner and Chair, Counties Transit Improvement Board, Minneapolis MN

Brian J. Lamb, General Manager, Metro Transit, Minneapolis, MN

Neil Pedersen, Executive Director, Transportation Research Board, Washington, DC

Kathryn D. Waters, Executive Vice President – Member Services, American Public Transportation Association, Washington, DC

Honorable Elizabeth "Betsy" Hodges, Mayor, Minneapolis, MN

General Session sponsored by HNTB Corporation

HNTB

9:15 – 10:45 a.m.
Great Lakes C
Fourth Floor


Metro Transit, Minneapolis, MN

Complete Streets

Complete streets policies, requiring that roadway designers consider the needs of all users, are increasingly being adopted in states, towns, and communities. Complete streets are credited with improving safety, providing environmental benefits, improving public health, revitalizing communities, and improving quality of life. Much of the focus has been on incorporating facilities for pedestrians and bicyclists. On the rare occasions when transit is considered, the assumption is that transit means buses. But to be "complete," these streets need to accommodate vehicles on rails. Light rail and streetcars require consideration of additional factors. How best are these modes incorporated into complete streets? What unique factors need to be considered?

Moderator
Monica J. Meade, Supervising Planner, WSP | Parsons Brinckerhoff, Baltimore, MD

Get Ready! Get Safety! Go! – Improving Safety in Street-Running Environments through Pre-Construction Analysis and Design
Kevin Jones, Systems Safety Manager, Parsons Transportation Group, Houston, TX

Trucks, Pedestrians, and Bicycles – Oh My! Improving Safety in Street Running and Mixed Use Environments
Walter Heinrich, Director of Safety, Metropolitan Transit Authority of Harris County, Houston, TX

Inserting Streetcars in Pedestrians Areas: French Examples Dominque Bertrand, Director of Studies of Urban Integration, Center-East Territory, Lyon, France

A Proposed Design Alternative for Inserting Dedicated Light Rail Transit Lanes and Other Facilities in a Constrained Arterial
Lyndon Henry, Transportation Planning Consultant, RAILWAY AGE, Austin, TX

9:15 – 10:45 a.m.
Lake Superior A&B
Fifth Floor

Metro Transit, Minneapolis, MN

State of the Art in Vehicles (LRT & Streetcar)

Starting with a synopsis of North American LRV and streetcar procurements over the last three years, this session presents solutions for several aspects of vehicle design, itemizes the growing list of technological advancements in alternative power supplies, and closes with a summary of real-world applications of one such approach, onboard energy storage systems, in operation, in development, and planned for streetcar projects in several U.S. cities.

Moderator
Thomas B. Furmaniak, P.E., Vice Chair, 13th National Light Rail & Streetcar Conference Planning Committee; Chair, APTA Light Rail Transit Technical Forum; and Managing Director, NDYLTK Rail, Sydney, Australia

North American LRV/Streetcar Procurements … since we last met
Thomas B. Furmaniak, P.E.

Ergonomics and Visibility in Tramway Driver's Cab
Alexandra Guesset, Engineer, Tramway Department, Technique des Remontées Mécaniques et des Transports Guidés (STRMTG), Saint-Martin-d'Hères, France

A Workable Solution for Conflicting Crashworthiness Requirements
Glenn Gough, Systems Engineer, Vehicle Structure & Calculations, Siemens Industry, Inc., Sacramento, CA

State-of-the-Art in Light Rail Alternatives
John Smatlak, Senior Consultant, Interfleet Technology Inc., Los Angeles, CA

John D. Swanson, Principal Consultant, Interfleet Technology Inc., Oceanside, CA

Onboard Energy Storage System Applications on Streetcar Projects
Jason M. Krause, P.E., Senior Engineer, LTK Engineering Services, Portland, OR

11 a.m. – 12:30 p.m.
Lake Superior A&B
Fifth Floor

Metro Transit, Minneapolis, MN

Ensuring LRT & Streetcar Safety

This session deals with the safety approach of light rail and streetcar systems, both from the point of view of the collection of data about accidents that happen to learn about their causes, and from the point of view of improving the layout design in order to develop a safer system. Presentations include perspectives from practice both in the United States and Europe.

Moderators
Pamela Fischhaber, Chief of Rail/Transit Safety, Colorado Public Utilities Commission, Denver, CO

Margarita Novales, Associate Professor, Railways and Transportation Group, University of A Coruña, Spain

Advancing Safety Rule Compliance: Proactive Safety Management through Simplified Data Analysis
Brian P. Dwyer, Senior Transportation Planner, Associate, STV Incorporated, Boston, MA

Michael Wiedecker, Director, Operations Training, Maryland Transit Administration, Baltimore, MD

LRT Safety: How are Pedestrians Involved?
Marine Millot, Head of Urban Road, Urban Safety and Lighting Section, CEREMA, Aix-en-Provence, France

Safety Management in Europe LRT Systems: Some Tools for Collecting and Using Accident Data
Dominique Bertrand, Senior Advisor, CEREMA, Lyon, France

Getting a Safer LRT Through Better Design of its Insertion in Public Space
Margarita Novales

11 a.m. – 12:30 p.m.
Great Lakes C
Fourth Floor


Metro Transit, Minneapolis, MN

Lessons Learned: The Price of Compromise

Funding even the needed elements of a start-up LRT system, before considering those elements desired by the operator and/or the community, is always a challenge. Compromises are inevitable to get a system up and running, and sometimes those compromises end up "kicking the can down the road." This session relates the experiences of three systems: Sacramento, Baltimore, and Denver, and the lessons each learned - sometimes from its preceding “start-up” as it expanded to meet service and community needs. Wrapping up the session, host system Metro Transit relates lessons learned as it developed procedures to respond to community requests for additional access to its Blue and Green Lines in metropolitan Minneapolis and St. Paul.

Moderator
Stephanie Eiler, Former Principal Transportation Planner and Vice President, CH2M, Minneapolis, MN

Compromise: A Necessary Element of Sacramento's LRT "Starter Line"
John Schumann, Senior Transportation Consultant-On Call, LTK Engineering Services, Portland, OR

Double-Tracking Baltimore’s Light Rail Transit System
Vernon G. Hartsock, PMP, Deputy Director, Engineering and Construction, Maryland Transit Administration, Baltimore, MD

Matthew Pollack, PE, PMP, Vice President, Southeast Division, HNTB Corporation, Baltimore, MD

Denver RTD’s Central Rail Corridor Capacity Improvements Eric Miller, Senior Rail Service Planner/Scheduler, Regional Transit District, Denver, CO

To Infill or Not to InFill: That is the Question
Mark Fuhrmann, Deputy General Manager, Transit System Development, Metro Transit, St. Louis Park, MN

MarySue Able, P.E., Deputy Project Director, Blue Line Extension, Metro Transit, Crystal, MN

12:45 – 2:15 p.m.
Great Lakes A&B
Fourth Floor

GENERAL LUNCHEON
Strategies & Tactics to Achieve Rapid Network Implementation

Presiding
Thomas B. Furmaniak, P.E., Vice Chair, 13th National Light Rail & Streetcar Conference Planning Committee; Chair, APTA Light Rail Transit Technical Forum; and Managing Director, NDYLTK Rail, Sydney, Australia

Sponsor Recognition
Kenneth P. Westbrook, Chairman, Transit Division & President, Rail Division, Transdev North America, Lombard, IL

Presenters
Aaron Isaacs, Transit Historian and Former Employee of Metro Transit, Minneapolis, MN

Adam Duininck, Chair, Metropolitan Council, St. Paul, MN

General Luncheon sponsored by Transdev North America

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2:30 – 4 p.m.
Great Lakes C
Fourth Floor

Maintenance Facility, Metro Transit, Minneapolis, MN

Procurement Strategies for LRT & Streetcar Systems

The speakers will discuss the strategies used for LRT & Streetcar procurements, such as Design-Bid-Build, Design-Bid and Construction Management/General Contractor. Each presenter will give a short overview of one of the strategies, followed by a panel discussion responding to questions from the moderator and audience.

Moderator
Harvey Berliner, Principal Consultant, HDR, Atlanta, GA

LRT Design Bid Build (DBB)
Dan Heller, Vice President, T.Y. Lin International, Inc., Tempe, AZ

LRT Design Build (DB)
Doug Jackson, Vice President of Transportation, WSB and Associates, Inc., Minneapolis, MN

LRT Construction
Mike Robertson, Owner, M.L. Robertson, LLC., Salt Lake City, UT

Experiences and Lessons Learned from the Maryland Purple Line Project – Streetcar Procurement Strategies
Gregory P. Benz, Senior Vice President, WSP | Parsons Brinckerhoff, Baltimore, MD

2:30 – 4 p.m.
Lake Superior A&B
Fifth Floor

Metro Transit, Minneapolis, MN

Insertion of Streetcars and LRTs in Urban Street Environments

With light rail transit already implemented along many under-utilized and abandoned rail corridors, metropolitan areas are increasingly looking to "insert" new rail lines directly into streets. This session will examine both historical and contemporary examples of how different urban areas in the U.S. and internationally have used the "insertion" approach to bring light rail transit into a variety of environments successfully. Speakers will focus on solutions to both physical and operational constraints.

Moderator
Jason Lee, Project Manager, San Francisco Municipal Transportation Agency, San Francisco, CA

Downtown Distribution for Light Rail Transit: Past, Present and Future
John Allen, Independent Transportation Consultant, Chicago, IL

Transit Signal Priority for LRT in a Complex Urban Environment
Dan Soler, P.E., Blue Line Extension Project Manager, Metro Transit, Minneapolis, MN

JoNette Kuhnau, PE, PTOE, Project Manager, Kimley-Horn and Associates, Inc., St. Paul, MN

Expanding MetroLink through Town Centers, Residential, and Urban Environments Across Greater Manchester
Dr. Jon Lamonte, Chief Executive, Transport for Greater Manchester, United Kingdom

Liz West, MetroLink Stakeholder Manager, Transport for Greater Manchester/WSP | Parsons Brinckerhoff, Manchester, UK

And They Said it Couldn't Be Done: Insertion of the Purple Line
Monica J. Meade, Supervising Planner, WSP | Parsons Brinckerhoff, Baltimore, MD

4:15 – 5:45 p.m.
Great Lakes C
Fourth Floor


Waterloo's Light Rail Car, Ontario, Canada

LRT & Streetcar Developments in Canada

LRT is on the move in Canada. Calgary and Edmonton continue to expand their networks, and a new fleet is entering revenue service in Toronto. Elsewhere in Ontario "new start" projects are underway in suburban Toronto, Ottawa, Ketchener/Waterloo, and Hamilton

Moderator
John Watkins, Senior Consultant, LTK Engineering Services, Toronto, ON

Seamless Mobility: The Design of Interchange Stations on the New Eglinton Crosstown LRT Line in Toronto
Americo Gonzalez, Senior Architect and Project Manager, HDR Corporation, Toronto, ON

ION Project Update
Thomas Schmidt, Commissioner, Transportation and Environmental Services, Regional Municipality of Waterloo, ON

4:15 – 5:45 p.m.
Lake Superior A&B
Fifth Floor

State of Good Repair

In North America, and indeed worldwide, light rail, streetcar, and tram transportation is experiencing a true renaissance. Maintaining State of Good Repair (SGR) of these systems as they age requires an ongoing process of condition assessment, regular monitoring, system maintenance, and renewal. Moreover, this involves a broad mix of assets, including infrastructure, rolling stock, and other important supporting systems. SGR is defined as the availability of assets in a condition suitable for the purpose for which they were intended. This session will cover some of the successful SGR activities and challenges that have been addressed in North America. Recent asset condition and end of asset life reporting requirements the FTA has established for transit properties to be eligible for federal funding will also be discussed.

Moderator
Tom O'Brien, Director of Business Development, KLD Labs, Inc., Hauppauge, NY

San Diego Trolley Renewal Program
John W. Haggerty, Director Rail Development, San Diego Association of Governments, San Diego, CA

SFMTA State of Good Repair Program – Twin Peaks Tunnel Trackway Improvement Project
Chuck Morganson, P.E., Associate Vice President, Senior Project Manager, HNTB Corporation, San Francisco, CA

Tess Kavanagh, Project Manager, San Francisco Municipal Transportation Agency, San Francisco, CA

"Want Your Money? What You Need to Know about Metrics for SGR with Regard to FTA Funding."
Martin P. Schroeder, M.S.M.E., P.E., Chief Technology Officer, American Public Transportation Association, Washington, DC

Impact of the Winter of 2015: Lessons the MBTA Learned for Maintaining State of Good Repair
William McClellan, Assistant General Manager of Rail Operations, Massachusetts Bay Transportation Authority, Boston, MA

Kimberly Woollard, Deputy Director of Light Rail Vehicle Maintenance & Engineering, Massachusetts Bay Transportation Authority, Boston, MA

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7 – 7:30 p.m.
Great Lakes C
Fourth Floor

Minneapolis Streetcar Alignment

A presentation of the proposed Minneapolis Streetcar Alignment on Nicollet Avenue across the river to NE Minneapolis.

Presenter
Nathan Koster AICP, Transportation Planner, City of Minneapolis, MN

Session sponsored by AECOM

7:30 – 9 p.m.
Great Lakes C
Fourth Floor

Open Forum

Bring your own 15 minute presentations regarding LRT and Streetcars

Moderator
James H. Graebner, Chair Emeritus, APTA Streetcar Subcommittee, and President, Lomarado Group, Denver, CO

Tuesday, November 17

7 – 11:15 a.m.
Great Lakes Promenade
Fourth Floor

Registration
Host/TRB/TCRP Information Desk

Cedar Room
Fourth Floor

Moderators/Speakers Room

7 – 7:45 a.m.
Great Lakes Promenade
Fourth Floor

Continental Breakfast

Breakfast sponsored by RATP Dev America

RATP Dev
AMERICA

7:15 – 7:45 a.m.
Lake Harriet
Fourth Floor

Conference Planning Committee Meeting

8 – 9:30 a.m.
Great Lakes B
Fourth Floor

LRT in the Total Transit System

LRT lines work best when integrated and coordinated with a region's other transit service, whether rail or bus or both. This session will examine the integration of new LRT lines into the fabric of an existing transit system in areas such as route network, schedules, fares, and coordination of radial, circumferential and crosstown routings.

Moderator
John Schumann, Senior Transportation Consultant-On Call, LTK Engineering Services, Portland, OR

Network Restructuring Around New High Capacity Service Ken Zatarain, Director of Service Delivery, Tri-County Metropolitan Transportation District of Oregon, Portland, OR

Integration of METRO Blue and Green Lines with Buses
John Dillery, Senior Transit Planner, Metro Transit, Minneapolis, MN

Importance of Bus Connections to Light Rail Accessibility Gains
Andrew Guthrie, Research Fellow, Humphrey School of Public Affairs, University of Minnesota, Minneapolis, MN

Light Rail Hubs in a Multimodal Transport Environment Martin Smoliner, Research Associate, Institute of Railway Engineering & Transport Economy, Graz University of Technology, Graz, Austria

Streetcar Institutional Models: A Comparison of Experience with Transit Coordination
Christopher Kopp, AICP, CTP, Transportation Planning Manager, HNTB Corporation, Chicago, IL

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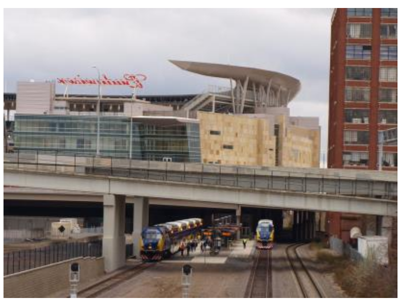
8 – 9:30 a.m.
Great Lakes A1–A3
Fourth Floor



Metro Transit, Minneapolis, MN

Infrastructure Developments

This session is a review of current issues and developments in light rail infrastructure design and implementation. Learn more about the latest in track design, traffic signal priority, structures, and conceptual planning guidelines for new LRT systems.

Moderator
Wulf Grote, P.E., Director, Planning & Accessible Transit, Valley Metro, Phoenix, AZ

Block Rail – Current Best Practices and Experiences on Recent Projects
Lucas L. Olson, P.E., Regional Streetcar Director, HDR Corporation, Minneapolis, MN

Transit Signal Priority Implementation in Phoenix
Jay Yenerich, P.E., Manager of Design, Valley Metro, Phoenix. AZ

LRT Structures
Jim Alexander, P.E., Director, Transit System Design & Engineering, Southwest LRT Project, Metro Transit, St. Louis Park, MN

Developing Infrastructure-Relevant Guidelines for Preliminary Conceptual Planning of a New Light Rail Transit System Lyndon Henry, Transportation Planning Consultant, RAILWAY AGE, Austin, TX

Session sponsored by AECOM

9:45 – 11:15 a.m.
Great Lakes C
Fourth Floor

Den Haag, Netherlands

Prague, Czech Republic

Oradea, Romania

Tramlink, East Croydon, England

EUROPEAN PANEL DISCUSSION
Successful Streetcar Design in Motorized Cities: Best Practices from Western and Eastern Europe

This plenary session examines recent thought on how large streetcar systems should adapt to serving regions where private ownership of automobiles has become, or will become, pervasive. We have three speakers intimately knowledgeable with these issues, one from western Europe and two from central Europe. Each will address recent experiences from their region, offering a case study of a major city as an illustration. We also have a discussant familiar with overall urban transport development in Europe who will tie the three presentations together.

Moderator
Dr. Michal Jaroszynski, Transportation Researcher, Department of Urban & Regional Planning, Florida State University, Tallahassee, FL

Welcome and Introductions
Dr. Gregory L. Thompson, Chair, TRB Light Rail Transit Committee, and Professor Emeritus, Transportation Planning, Department of Urban & Regional Planning, Florida State University, Tallahassee, FL

RandstadRail, an Integrated Light Rail and Metro System in the Metropolitan Region Rotterdam - The Hague
Leonardus H. Haring, Vice Chair, UITP LRT Committee, and Director, HRL Consultancy, The Hague, The Netherlands

The Key Directions of the Modernization of Tram Systems in Central and Eastern European Countries (CEEC)
Gradimir Stefanovic, Managing Director, GS Transport Consultancy Ltd., London, United Kingdom

Integrated Urban Mobility Plans: A Key of LRT Systems Survival and Renaissance
Dr. István Csuzi, General Manager, Oradea Transport Local S.A., Oradea, Romania

Lessons for Public Policy
Dr. Michal Jaroszynski

APPENDIX B

List of Attendees

Mary Sue Abel
Metro Transit
St. Louis Park, Minnesota
marysue.abel@metrotransit.org

Alex Abraham
The Reinforced Earth Company
Aurora, Illinois
aabraham@reinforcedearth.com

Jim Alexander
Metro Transit
St. Louis Park, Minnesota
jim.alexander@metrotransit.org

John G. Allen
jgatransit@2200.com

Don Allison
Tri-County Metropolitan Transportation District of Oregon (TriMet)
Portland, Oregon
allisond@trimet.org

Raymond Amoruso
Hampton Roads Transit
Norfolk, Virginia
ramoruso@hrtransit.org

Ken J. Anderson
RNL Design
McLean, Virginia
ken.anderson@rnldesign.com

Steve Andrle
Transportation Research Board
Washington, D.C.
sanderle@nas.edu

Steven C. Apanian
LTK Engineering Services
Minneapolis, Minnesota
sapanian@ltk.com

Americo Gonzalez Aquino
HDR
Richmond Hill, Ontario, Canada
Americo.GonzalezAquino@hdrinc.com

Yoshitaka Araki
Japan International Transport Institute
Washington, D.C.
araki@japantransport.com

Andrea Arnoldi
Kimley-Horn and Associates, Inc.
Herndon, Virginia
andrea.arnoldi@kimley-horn.com

Ted Axt
AECOM
Minneapolis, Minnesota
ted.axt@aecom.com

James Baker
Connetics Transportation Group, Inc.
Roswell, Georgia
jbaker@ctgconsult.com

Edward Baldzicki
Xerox State & Local Solutions, Inc.
Germantown, Maryland
edward.baldzicki@xerox.com

Jay Banasiak
El Paso Mass Transit Department
(Sun Metro)
El Paso, Texas
banasiakJ1@elpasotexas.gov

Michael Benham
Ann Arbor Area Transportation Authority
Ann Arbor, Michigan
mbenham@aata.org

Gregory P. Benz
WSP–Parsons Brinckerhoff
Baltimore, Maryland
benz@pbworld.com

Martin J. Benzaquen
Gannett Fleming, Inc.
Miami, Florida
mbenzaquen@gfnet.com

Harvey L. Berliner
HDR
Atlanta, Georgia
harvey.berliner@hdrinc.com

Dominique Bertrand
Cerema
Paris, France
dominique.bertrand@cerema.fr

Steve Bethel
RATP Dev America
New York, New York
steve.bethel@tucsonaz.gov

Donald L. Billen
Sound Transit
Seattle, Washington
don.billen@soundtransit.org

Mark Bishop
Kimley-Horn and Associates, Inc.
St. Paul, Minnesota
mark.bishop@kimley-horn.com

Lonnie Blaydes
Herzog Transit Services, Inc.
St. Joseph, Missouri
Lblaydes@htsi.com

Stephen Bonina
Stadler US Inc.
Westfield, New Jersey
stephen.bonina@stadlerrail.com

Jeffrey F. Boothe
Boothe Transit Consulting, LLC
Washington, D.C.
jeff.boothe@boothetransit.com

Robert Bostian, Jr.
Florida Department of Transportation
Ft. Lauderdale, Florida
robert.bostian@dot.state.fl.us

Charlie Boudakian
Magnetic Sensors Corporation
Anaheim, California
cboudakian@magsensors.com

David Bouwkamp
FAAC Incorporated
Ann Arbor, Michigan
Development
dsb@faac.com

Winsome Anne Bowen
EAC Consulting, Inc.
Miami, Florida
jortega@eacconsult.com

Marcelo Bravo
Trapeze Group
Columbia, Maryland
victoria.fulton@trapezegroup.com

Keith Brown
Interfleet Technology Inc.
New York, New York
keith.brown@snclavalin.com

Peter Bruno
Transportation Resource Associates, Inc.
Philadelphia, Pennsylvania
peter.bruno@traonline.com

Christopher Bucknor
EAC Consulting, Inc.
Miami, Florida
nquinones@eacconsult.com

Brian W. Budzynski
Roads & Bridges/TM&E
Arlington Heights, Illinois
bbudzynski@sgcmail.com

Martin Bussiere
ABB Inc.
Lachine, Quebec, Canada
martin.b.bussiere@ca.abb.com

Edward Byers
Herzog Transit Services, Inc.
Austin, Texas
ebyers@htsi.com

Richard A. Carman
Wilson, Ihrig & Associates, Inc.
New York, New York
rcarman@wiai.com

David Caron
ABB Inc.
Lachine, Quebec, Canada
david.b.caron@ca.abb.com

Meredith Carter
Voith Turbo Inc.
York, Pennsylvania
meredith.carter@voith.com

Linton Castle
voestalpine Nortrak Ltd.
Richmond, British Columbia, Canada
linton.castle@voestalpine.com

Frank Cegelski
Magnetic Sensors Corporation
Anaheim, California
fcegelski@magsensors.com

Carole Cej
City of Edmonton
Edmonton, Alberta, Canada
christiann.labrie@edmonton.ca

Melda Cermi
Alstom Transport Canada Inc.
Montreal, Quebec, Canada
melda.cermi@transport.alstom.com

Shormila Chatterjee
SNC-Lavalin Inc.
Vancouver, British Columbia, Canada
shormila.chatterjee@snclavalin.com

Eva Cheung
Edmonton Transit System
Edmonton, Alberta, Canada
eva.cheung@edmonton.ca

Barry R. Chown
San Francisco Municipal Transportation Agency
San Francisco, California
barry.chown@sfmta.com

Steve Clark
ED Agency
Cambridge, Massachusetts
steveclark@edagency.net

Michael Comis
Telephonics Corporation
Farmingdale, New York
comis@telephonics.com

Sean Coster
Plan Group Inc.
Vaughan, Ontario, Canada
scoster@plan-group.com

Dylan Counts
Washington State Department of Transportation
Olympia, Washington
countsd@wsdot.wa.gov

Scott Crego
voestalpine Nortrak Ltd.
Richmond, British Columbia, Canada
scott.crego@voestalpine.com

Kevin J. Cronin
Gannett Fleming, Inc.
Baltimore, Maryland
kcronin@gfnet.com

Istvan Csuzi
Oradea Transport Local S.A.
Oradea, Romania
secretariat@otl.ro

Paul B. Danielson
Kimley-Horn and Associates, Inc.
St. Paul, Minnesota
paul.danielson@kimley-horn.com

Eric Denis
ABB Inc.
Lachine, Quebec, Canada
eric.denis@ca.abb.com

Paul Denison
Sound Transit
Seattle, Washington
Paul.Denison@soundtransit.org

John Dillery
Metro Transit
Minneapolis, Minnesota
john.dillery@metrotransit.org

John Doan
Hennepin County Regional Railroad Authority
Minneapolis, Minnesota
jackie.rock@hennepin.us

Dave Dobbs
Light Rail Now!
Texas Association for Public Transportation
Austin, Texas
publisherlrn@gmail.com

Mark L. Dorn
AECOM
Portland, Oregon
Mark.Dorn@aecom.com

Brian P. Dwyer
STV Incorporated
Boston, Massachusetts
brian.dwyer@stvinc.com

Joe Ebsen
AECOM
New York, New York
joe.ebsen@aecom.com

Stephanie Cyr Eiler
scemiquelon@gmail.com

Paul D. Elman
Kimley-Horn and Associates, Inc.
Reston, Virginia
paul.elman@kimley-horn.com

Marcus Eng
American Public Transportation Association
Washington, D.C.
meng@apta.com

Igan Erostarbe
CAF USA, Inc.
Washington, D.C.
igan.erostarbe@cafusa.com

David Eyles
SNC-Lavalin O&M
Toronto, Ontario, Canada
david.eyles@snclavalinom.com

Stanley G. Feinsod
First Transit
Bluffton, South Carolina
stanfeinsod@astound.net

Jason Ferbrache
Embark
Oklahoma City, Oklahoma
jason.ferbrache@okc.gov

Dwight Ferrell
Southwest Ohio Regional Transit Authority/Metro
Cincinnati, Ohio
dferrell@go-metro.com

Pamela Fincher
HNTB Corporation
Atlanta, Georgia
pfincher@hntb.com

Pamela Fischhaber
Colorado Public Utilities Commission
Denver, Colorado
pamela.fischhaber@state.co.us

Tracy Fosmo
Kimley-Horn and Associates, Inc.
St. Paul, Minnesota
tracy.fosmo@kimley-horn.com

Linnea L. Frary
voestalpine Nortrak, Inc.
Seattle, Washington
linnea.frary@voestalpine.com

Keith Frazier
Faiveley Transport North America
Greenville, South Carolina
keith.frazier@faiveleytransport.com

Mark Fuhrmann
Metro Transit
St. Louis Park, Minnesota
mark.fuhrmann@metrotransit.org

Thomas B. Furmaniak
LTK Engineering Services
Ambler, Pennsylvania
tfurmaniak@ltk.com

Jeff Galbraith
AECOM
Minneapolis, Minnesota
jeffrey.galbraith@aecom.com

Kevin Garben
Thales Transport & Security, Inc.
Pittsburgh, Pennsylvania
kevin.garben@us.thalesgroup.com

Brandon Gasiewicz
Faiveley Transport North America
Greenville, South Carolina
brandon.gasiewicz@faiveleytransport.com

James Gersema
SRF Consulting Group, Inc.
Minneapolis, Minnesota
jgersema@srfconsulting.com

Dennis Gian
Magnetic Sensors Corporation
Anaheim, California
dgian@nycap.rr.com

Lee G. Gibson
Regional Transportation Commission of Washoe County
Reno, Nevada
lgibson@rtcwashoe.com

Matt Gibson
Kimley-Horn and Associates, Inc.
Tampa, Florida
matt.gibson@kimley-horn.com

Shellie Ginn
City of Tucson Transit Services Division
Tucson, Arizona
shellie.ginn@tucsonaz.gov

Gordon Glass
First Transit, Inc.
Cincinnati, Ohio
gordon.glass@firstgroup.com

Glenn Gough
Siemens Industry, Inc.: Mobility Division
Sacramento, California
patricia.anaya@siemens.com

Oleg Goureev
ABB Inc.
Lachine, Quebec, Canada
ogoureev@gmail.com

James H. Graebner
Lomarado Group
Denver, Colorado
carbarn@aol.com

Shaun Green
Atlanta BeltLine, Inc.
Atlanta, Georgia
sgreen@atlbeltline.org

Wulf Grote
Valley Metro
Phoenix, Arizona
wgrote@valleymetro.org

Alexandra Guesset
STRMTG
Saint-Martin-d'Hères, France
alexandra.guesset@developpement-durable.gouv.fr

Levi Gustin
Optimation Technology Inc.
Louisville, Colorado
levi.gustin@optimation.us

Andrew Guthrie
University of Minnesota
Minneapolis, Minnesota

Michael Habouri
ABB Inc.
Lachine, Quebec, Canada
michael.g.habouri@ca.abb.com

John W. Haggerty
San Diego Association of Governments
San Diego, California
mpo@sandag.org

Milan Haloun
Inekon Group, a.s.
Prague, Czech Republic
haloun@inekon.cz

Gary A. Hamm
The Solis Group
Pasadena, California
ghamm@thesolisgroup.com

Leonardus Haring
HLR Consultancy
The Hague, Netherlands
l.haring@htm.net

Peter J. Harper
Harper Consulting
Murrysville, Pennsylvania
pjah73@gmail.com

Thomas Robert Harrington
Kimley-Horn and Associates, Inc.
Herndon, Virginia
tom.harrington@kimley-horn.com

Preeti Harris
Lea+Elliott, Inc.
Dulles, Virginia
pharris@leaelliott.com

Shaun Harris
voestalpine Nortrak, Inc.
Birmingham, Alabama
shaun.harris@voestalpine.com

Brian Hawkins
Siemens Industry, Inc.: Mobility Division
Sacramento, California
bhawkins@siemens.com

Walter Heinrich
Metropolitan Transit Authority of Harris County
Houston, Texas
Walter.Heinrich@ridemetro.org

Lyndon Henry
RAILWAY AGE
New York, New York
nawdry@gmail.com

Robert C. Highfill
Jacobs
Walnut Creek, California
robert.highfill@jacobs.com

Mark Hill
ALSTOM Signaling Inc.
West Henrietta, New York
mark.hill@transport.alstom.com

Charles H. Hinton, Jr.
C3M Power Systems LLC
Capitol Heights, Maryland
chuck.hinton@c3mpowersystems.com

George M. Hitchcock III
Hatch Mott MacDonald
Atlanta, Georgia
george.hitchcock@hatchmott.com

Jon Holler
Maintenance Design Group, LLC
Pasadena, California
jon.holler@mdg-llc.com

Brian Holt
bholt@ascentsignal.com

Rob Hume
Kimley-Horn and Associates, Inc.
Raleigh, North Carolina
rob.hume@kimley-horn.com

Charles Matthew Hymes, Jr.
WSP–Parsons Brinckerhoff
Orlando, Florida
HymesCM@pbworld.com

Ofuonye Comfort Ifechukwude
Lagos State University
Lagos, Nigeria
com_ify@yahoo.com

Kenji Inomata
Mitsubishi Electric Research Lab
Cambridge, Massachusetts
inomata@merl.com

Andreas Isler
ABB Inc.
Turgi, Switzerland
andreas.isler@ch.abb.com

Michal Jaroszynski
mjaroszynski@fsu.edu

Soren Jensen
Midtown Greenway Coalition
Minneapolis, Minnesota
soren@midtowngreenway.org

David F. Jickling
Regional Transportation Commission
of Washoe County
Reno, Nevada
djickling@rtcwashoe.com

Kevin Jones
Parsons Corporation
Baltimore, Maryland
kevin.jones@parsons.com

Charles V. Joseph
American Public Transportation Association
Washington, D.C.
cjoseph@apta.com

Nguvi Kahiha
Consultant
Smyrna, Georgia
ngkahiha@hotmail.com

Bart Kane
AECOM
Dallas, Texas
bart.kane@aecom.com

Brian Kim
AECOM
Minneapolis, Minnesota
Brian.kim@aecom.com

Ken Klem
IMPulse NC LLC
Mount Olive, North Carolina
kklem@impulsenc.com

Philip Michael Klinkon
RNL Design
Los Angeles, California
phil.klinkon@rnldesign.com

Christopher Kopp
HNTB Corporation
Chicago, Illinois
ckopp@hntb.com

Zoltan Kovacs
Wabtec Corporation
Spartanburg, South Carolina
zkovacs@wabtec.com

Eric Kozlowski
Thales Transport & Security, Inc.
Pittsburgh, Pennsylvania
eric.kozlowski@us.thalesgroup.com

Joseph Kresse
K-Technologies Inc.
Minneapolis, Minnesota
ktechinc@gmail.com

Richard A. Krisak
Metropolitan Atlanta Rapid Transit Authority
Atlanta, Georgia
RKrisak@itsmarta.com

JoNette Kuhnau
Kimley-Horn and Associates, Inc.
Herndon, Virginia
jonette.kuhnau@Kimley-Horn.com

Brian J. Lamb
Metro Transit
Minneapolis, Minnesota
brian.lamb@metrotransit.org

Jeffrey LaMora
Utah Transit Authority
Salt Lake City, Utah
jlamora@rideuta.com

Son Tran Lamson
SNC-Lavalin Inc.
Vancouver, British Columbia, Canada
son.lamson@snclavalin.com

Angie Laurie
Atlanta Downtown
Improvement District, Inc.
Atlanta, Georgia
alaurie@atlantadowntown.com

Jason Lee
San Francisco Municipal Transportation Agency
San Francisco, California
jasonrlee@yahoo.com

Mark Leemon
Metro Transit
Minneapolis, Minnesota
mark.leemon@metrotransit.org

Donald J. Leidy
Maintenance Design Group, LLC
Denver, Colorado
don.leidy@mdg-llc.com

William Lieberman
CHS Consulting Group
San Francisco, California
w.lieberman100@gmail.com

Benjamin Limmer
Atlanta BeltLine, Inc.
Atlanta, Georgia
blimmer@atlbeltline.org

George Long
Siemens Industry, Inc.: Mobility Division
Sacramento, California
george.long@siemens.com

Murphy Madison
CAF USA, Inc.
Washington, D.C.
murphy.madison@cafusa.com

Steve Mahowald
Metro Transit
Minneapolis, Minnesota
steve.mahowald@metrotransit.org

Jack Martinson
ALSTOM Transportation Inc.
New York, New York
jack.martinson@transport.alstom.com

Alane Masui
Sacramento Regional Transit District
Sacramento, California
amasui@sacrt.com

Jom Mata
Kimley-Horn and Associates, Inc.
St. Paul, Minnesota
jom.mata@kimley-horn.com

Brandon Mark Maurisak
AECOM
Minneapolis, Minnesota
brandon.maurisak@aecom.com

Steve Mazur
Digi International
Minnetonka, Minnesota
steve.mazur@digi.com

Jack McDowell
Jack McDowell Transit Consultant
Long Beach, California
jmcdtc87@yahoo.com

Joel McNeil
Brookville Equipment Corp.
Brookville, Pennsylvania
jmcneil@brookvillecorp.com

Monica J. Meade
WSP–Parsons Brinckerhoff
Baltimore, Maryland
meade@pbworld.com

Rick Meade
Los Angeles County Metropolitan
Transportation Authority
Chatsworth, California
meader@metro.net

Lance D. Meister
Cross-Spectrum Acoustics LLC
Waltham, Massachusetts
lmeister@csacoustics.com

Sayaja Fukahori Mensah
Japan International Transport Institute
Washington, D.C.
fukahori@japantransport.com

Kirit Mevawala
Louis Berger
Morristown, New Jersey
kmevawala@louisberger.com

Eric Miller
Regional Transportation District
Denver, Colorado
eric.miller@rtd-denver.com

Marine Millot
Cerema
Paris, France
marine.millot@cerema.fr

William H. Moorhead
Smithfield, Virginia
trammco@mindspring.com

Chuck Morganson
HNTB Corporation
San Francisco, California
CMorganson@HNTB.com

John Morrison
Toronto Transit Commission
Toronto, Ontario, Canada
john.morrison@ttc.ca

Santiago Muniz
Balfour Beatty Infrastructure, Inc.
West Covina, California
smuniz@bbiius.com

Angela Murphy
Minnesota Department of Transportation
Roseville, Minnesota
angela.murphy@state.mn.us

Carl Natvig
San Francisco Municipal Transportation Agency
San Francisco, California
carl.natvig@sfmta.com

Richard H. Nau
Kimley-Horn and Associates, Inc.
Baltimore, Maryland
Rick.Nau@kimley-horn.com

Julie Navarrete
Hampton Roads Transit
Hampton, Virginia
jnavarrette@hrtransit.org

Jim Neal
PGH Wong Engineering, Inc.
San Diego, California
jneal@pghwong.com

Curtis R. Neft
Kimley-Horn and Associates, Inc.
Raleigh, North Carolina
Curtis.neft@kimley-horn.com

Derek Newbauer
Kimley-Horn and Associates, Inc.
St. Paul, Minnesota
derek.newbauer@kimley-horn.com

Joe Nietfeld
Minnesota Department of Transportation
Roseville, Minnesota
joe.nietfeld@state.mn.us

Mark R. Nordling
Transportation Technology Center, Inc.
Pueblo, Colorado
mark_nordling@aar.com

Margarita Novales
University of A Coruña
A Coruña, Spain
mnovales@udc.es

Thomas O'Brien
KLD Labs, Inc.
Hauppauge, New York
tobrien@kldlabs.com

Okam Cletus Obua
Lagos State University
Lagos, Nigeria
okamcletus@yahoo.com

Steven Marc Ojalvo
ABB Inc.
Lachine, Quebec, Canada
steven.ojalvo@ca.abb.com

Lucas L. Olson
HDR
Minneapolis, Minnesota
lucas.olson@hdrinc.com

Richard Palmieri
AECOM
Atlanta, Georgia
richard.palmieri@aecom.com

Philip G. Pasterak
WSP–Parsons Brinckerhoff
Chicago, Illinois
pasterak@pbworld.com

Neil Pedersen
Transportation Research Board
Washington, D.C.
npedersen@nas.edu

Joe Perrotta
City of Mississauga
Mississauga, Ontario, Canada
joe.perrotta@mississauga.ca

Michael H. Perry
Sound Transit
Seattle, Washington
michael.perry@soundtransit.org

Dave Pesch
Rochester–Olmsted Planning Department
Rochester, Minnesota
pesch.dave@co.olmsted.mn.us

David F. Peterson
Parsons Corporation
Minneapolis, Minnesota
petersondf@pbworld.com

Joanne Peterson
Los Angeles County Metropolitan
Transportation Authority
Los Angeles, California
petersonjo@metro.net

Jeffrey S. Polenske
City of Milwaukee
Milwaukee, Wisconsin
jpolen@milwaukee.gov

Matthew W. Pollack
HNTB Corporation
Atlanta, Georgia
mpollack@hntb.com

James E. Price
Hampton Roads Transit
Hampton, Virginia
jprice@hrtransit.org

Kimberly Proia
AECOM
Minneapolis, Minnesota
kimberly.proia@aecom.com

Andreas Rakebrandt
INIT Innovations in Transportation Inc.
Chesapeake, Virginia
arakebrandt@initusa.com

Claire Randall
Transportation Research Board
Washington, D.C.
crandall@nas.edu

Jeffrey Rankin
CH2M
Toronto, Ontario, Canada
jeffrey.rankin@ch2m.com

Lisa Rasmussen
Kimley-Horn and Associates, Inc.
Raleigh, North Carolina
lisa.rasmussen@kimley-horn.com

Scott Reichert
CAF USA, Inc.
Washington, D.C.
scott.reichert@cafusa.com

Marina Lagune Reutler
University of Minnesota
Minneapolis, Minnesota
lagun011@umn.edu

Timothy Reynolds
WSP–Parsons Brinckerhoff
Cincinnati, Ohio
reynoldsti@pbworld.com

George W. Ritter
EWI
Columbus, Ohio
gritter@ewi.org

Will Roberson
IMPulse NC LLC
Mount Olive, North Carolina
wroberson@impulsenc.com

Michael L. Robertson
Collaborative Solutions
Salt Lake City, Utah
mrobertson@col-sol.com

Bryan Romrell
Utah Transit Authority
Salt Lake City, Utah
bromrell@rideuta.com

Theodore Rosenbaum
LTK Engineering Services
San Francisco, California
trosenbaum@ltk.com

Albert Salas
Florida Department of Transportation
Ft. Lauderdale, Florida
albert.salas@dot.state.fl.us

Dyanne A. Sampson
Hampton Roads Transit
Hampton, Virginia
dsampson@hrtransit.org

Eric Schook
Ansaldo STS USA, Inc.
Pittsburgh, Pennsylvania
eschook@railliance.com

Barbara M. Schroeder
ALSTOM Transportation Inc.
New York, New York
barbara.schroeder@alstom.com

Martin P. Schroeder
American Public Transportation Association
Washington, D.C.
mschroeder@apta.com

John Schumann
LTK Engineering Services
Portland, Oregon
jschumann@ltk.com

Chris Searles
BAE Batteries USA
Somerset, Wisconsin
715-247-2262

Michael H. Setzer
Transdev North America
Garden City, New York
michael.setzer@transdev.com

Abdul Waheed Shaikh
City of Mississauga
Mississauga, Ontario, Canada
abdul.shaikh@mississauga.ca

Scott Sherin
ALSTOM Transportation Incorporated
Hornell, New York
scott.sherin@transport.alstom.com

Brendon Simon
Region of Waterloo
Kitchener, Ontario, Canada
bsimon@regionofwaterloo.ca

Daniel Simounet
ABB Inc.
Lachine, Quebec, Canada
daniel.simounet@ca.abb.com

Eric Simpson
Go Triangle
Research Triangle Park, North Carolina
esimpson@gotriangle.org

Jody Sims
Stacy and Witbeck, Inc.
Alameda, California
jsims@stacywitbeck.com

Olga Sisamon
CAF USA, Inc.
Washington, D.C.
olga.sisamon@cafusa.com

John Smatlak
Interfleet Technology Inc.
Los Angeles, California
smatlak.j@interfleetinc.com

Paul Smith
Telephonics Corporation
Farmingdale, New York
smithp@telephonics.com

Martin Smoliner
Graz University of Technology–Austria
Graz, Austria
martin.smoliner@tugraz.at

Daniel Soler
Metro Transit
Minneapolis, Minnesota
dan.soler@metrotransit.org

Georgina Stanley-Woidyla
SRF Consulting Group, Inc.
Minneapolis, Minnesota
gstanley@srfconsulting.com

Gradimir Stefanovic
GS Transport Consultancy
London, United Kingdom
stefgrad@gstc.fsnet.co.uk

Richard D. Stewart
University of Wisconsin-Superior
Superior, Wisconsin
rstewart@uwsuper.edu

Peter Straus
San Francisco Municipal Transportation Agency
San Francisco, California
pstrausSF@prodigy.net

Astrid Stumpf
ALSTOM Transportation Inc.
New York, New York
astrid.stumpf@transport.alstom.com

Kevin Sudano
RSM Services, Clever Devices
Stafford, Texas
ksudano@rsmservices.com

Lee Summerlott
San Francisco Municipal Transportation Agency
San Francisco, California
lee.summerlott@sfmta.com

John D. Swanson
Interfleet Technology Inc
Oceanside, California
swanson.j@interfleetinc.com

John Carl Swartz
AECOM
Los Angeles, California
john.swartz@aecom.com

Michael A. Tagaras
LTK Engineering Services
Highland Village, Texas
mtagaras@ltk.com

Gregory L. Thompson
Florida State University
Tallahassee, Florida
glthompsn@fsu.edu

Le Hoang Tien
University of Stuttgart
Stuttgart, Germany
lehoangtienkshtdt@yahoomail.com

Jitendra S. Tomar
CAF USA, Inc.
Washington, D.C.
tomar@cafusa.com

David A. Towers
Harris Miller Miller & Hanson Inc.
Burlington, Massachusetts
dtowers@hmmh.com

Michael S. Townes
HNTB Corporation
Arlington, Virginia
mtownes@hntb.com

Richard E. Trail
Siemens Industry, Inc.: Mobility Division
Bridgeville, Pennsylvania
richard.trail@siemens.com

Bill Umbenhaur
Traction Systems
Somerville, New Jersey
bill.umbenhaur@tractionsystems.com

Daria van Engelen
Serco Inc.
Reston, Virginia
daria.vanengelen@serco-na.com

Roy Van Wynsberghe
Voith Turbo Inc.
York, Pennsylvania
Roy.Van-Wynsberghe@voith.com

Steven R. Vecerina
AECOM
Jersey City, New Jersey
steven.vecerina@aecom.com

Virginia Verdeja
CAF USA, Inc.
Washington, D.C.
virginia.verdeja@cafusa.com

Kevin Vokey
SNC-Lavalin Inc.
Vancouver, British Columbia, Canada
kevin.vokey@snclavalin.com

Jon H. Walter
era-contact USA, LLC
Hauppauge, New York
j.walter@era-contact.us

Alan Wapner
Southern California Association of Governments
Los Angeles, California
awapner@ci.ontario.ca.us

Kathryn D. Waters
American Public Transportation Association
Washington, D.C.
kwaters@apta.com

John Watkins
LTK Engineering Services
Ambler, Pennsylvania
jwatkins@ltk.com

Patrick J. Watz
HNTB Corporation
Golden Valley, Minnesota
pwatz@hntb.com

Randal Weaver, Sr.
Southwest Ohio Regional Transit
Authority/Metro
Cincinnati, Ohio
rweaver@go-metro.com

Kenneth P. Westbrook
Transdev North America
Lombard, Illinois
ken.westbrook@transdev.com

Christopher Paul Weyer
HNTB Corporation
Golden Valley, Minnesota
cweyer@hntb.com

Jeffrey Wharton
IMPulse NC LLC
Mount Olive, North Carolina
jwharton@impulsenc.com

Michael White
Brookville Equipment Corp.
Brookville, Pennsylvania
mwhite@brookvillecorp.com

Blake Whitson
Center for Transportation
and the Environment
Atlanta, Georgia
Steve@cte.tv

Michael Wiedecker
Maryland Transit Administration
Baltimore, Maryland
knelson1@mta.maryland.gov

Carl W. Wikse
Saft
Cockeysville, Maryland
carl.wikse@saftbatteries.com

Andrew Wilkins
ABB Inc.
Pointe-Claire, Quebec, Canada
andrew.wilkins@ca.abb.com

John D. Wilkins
wilkinsjd@aol.com

Helena E. Williams
RATP Dev America
New York, New York
helena.williams@ratpdev.com

Peggy Wilson
American Public Transportation Association
Washington, D.C.
pwilson@apta.com

Ryan Wilson
Minnesota Department of Transportation
Roseville, Minnesota
ryan.wilson@state.mn.us

David E. Wohlwill
Port Authority of Allegheny County
Pittsburgh, Pennsylvania
dwohlwill@portauthority.org

Darwin Yasis
WSP–Parsons Brinckerhoff
Chicago, Illinois
yasisd@pbworld.com

Jay Yenerich
Valley Metro
Phoenix, Arizona
jyenerich@valleymetro.org

Ken Zatarain
Tri-County Metropolitan Transportation District of Oregon
Portland, Oregon
zataraik@trimet.org

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TRB
TRANSPORTATION RESEARCH BOARD
500 Fifth Street, NW
Washington, DC 20001