Light Rail/Traffic Interface in Portland: The First Five Years

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In 1986 a new 15-mi-long light rail transit (LRT) line began operating in Portland, serving a corridor between downtown and the eastern suburb of Gresham. This line uses a variety of rights-of-way, operating in city streets, in the median of a street, and on exclusive right-of-way. Of the intersections, 55 have traffic signals, 9 are gated, and 7 use stop signs to control cross traffic. The initial concepts that guided design of the light rail/traffic interface were drawn selectively from U.S. and European concepts with emphasis on adapting existing railroad and traffic control hardware to what were perceived as the needs of LRT. Since operations began, Tri-Met has closely monitored system safety and has developed remedial measures where accident patterns have been identified. Several potential problems were identified during design and fixed before revenue service started. These included the need for LRT traffic signal aspects that would not be misread by motorists, control of right turns on red, and the limitations of changeable message signs. A number of lessons can be drawn from the Portland experience. LRT can be inserted into the street network and operate harmoniously with other traffic, achieving increases in the people-moving capacity of the central area streets. For the most part, existing traffic signal hardware and control techniques can be adapted for light rail/traffic interface in a cost-effective manner. The closure of streets for construction and the changed configurations following construction offer the opportunity to rearrange traffic patterns to diminish the impact on traffic, particularly in central areas. And saving initial construction costs by compromising traffic design (for instance, by omitting a lightly used turn lane) must be weighed against possible future operating problems.

With a population of about 1.1 million, the Portland region is the largest urbanized area in Oregon. Public transportation in Portland is provided by the Tri-County Metropolitan Transportation District of Oregon, more commonly known as Tri-Met, which operates a fleet of some 450 buses and 26 light rail cars and carries about 55 million boarding trips per year.

In 1986 Tri-Met completed a light rail transit (LRT) line serving the corridor between the Portland central business district (CBD) and the eastern suburb of Gresham, a distance of about 15 mi. This line uses a variety of rights-of-way, including on-street operation (usually in reserved lanes), street medians, and segments of exclusive right-of-way, some of them grade separated.

The concepts that guided the design can now be reviewed from the vantage point of 5 years experience along with changes made to improve operations or safety. Much of this experience is being incorporated into Portland's second light rail line, the design of which is now in progress.

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DESIGN CONCEPTS

When the design of Portland's Banfield light rail project began in the early 1980s, little precedent for modern LRT in the United States existed. Tri-Met's initial design was developed by drawing selectively from U.S. and European examples of LRT and traffic control concepts, with particular emphasis on adapting existing railroad and traffic control hardware to the perceived needs of an LRT system. Because streetcars had not operated in Portland for 30 years, it was also necessary to develop a new regulatory framework to define the powers and responsibilities of the local jurisdictions and the state public utility commissioner.

Regulatory Context

Prior to the light rail project, state law specifically exempted transit agencies from regulation by the Oregon Public Utility Commission (OPUC) with the exception of rail grade crossings. The law was silent on how typical LRT configurations, such as traffic signal controlled intersections not found on railroads, should be designed and regulated. To resolve this issue, Tri-Met and the local jurisdictions worked with OPUC to develop amending legislation that defined how the various types of crossings used on LRT should be regulated. The amended legislation states that light rail grade crossings are regulated by OPUC in the same manner as railroad grade crossings *unless* the light rail line operates within and parallel to a street right-of-way and conventional traffic control devices are used. At such locations the crossings are subject to the local traffic jurisdiction. In effect, if the LRT operates as part of the general traffic circulation system, it is governed by the general traffic circulation regulations. If an LRT crossing operates like a railroad crossing, it is regulated by OPUC in the same manner as other rail crossings.

Preempt and Traffic Circulation

The traffic design developed around preempt policies specific to each segment of the line. On the suburban segment, where intersections are generally spaced (at about 0.25-mi intervals), the LRT operates with full priority over other traffic. Both gated and signalized intersections are used, depending on site configuration and design speed.

To insert the LRT into the relatively complex traffic network in the CBD with the least impact, it was necessary to integrate train movements into the existing traffic signal pro-

gressions to the greatest possible extent. So long as the train moves with the progression, it has very little impact on traffic. However, when it stops, it becomes disconnected from the progression. Under this design concept, a train must wait for the traffic signal progression before leaving a station but, once moving within the progression, can expect to reach the next station without stopping.

As in most metropolitan areas, the local traffic jurisdictions were concerned that street capacity not be lost or traffic delayed. Therefore an important design guideline was to preserve traffic flow and capacity to the greatest possible extent. Where LRT required a change in traffic patterns, localized traffic studies were made to predict the impact and develop mitigation measures. This approach overlooked one highly important consideration. The construction of the LRT required the affected streets be closed to through traffic for extended periods, often up to a year. This forced the modification of traffic flow patterns on alternative streets. After construction, the traffic that returned to the streets where LRT operates was only the traffic that found the reopened streets more convenient. Consequently much greater flexibility could probably have been used in designing the traffic circulation concept and greater advantage derived from LRT as a tool to promote traffic calming.

Traffic Signal Hardware

An early design policy was to equip all public vehicular crossings of LRT tracks with active traffic control devices that clearly assign right-of-way between the conflicting movements. This was later modified in the downtown area to allow stop sign control at a number of minor intersections where LRT operating speeds are low.

Throughout the design, simplicity of concept and operation, avoidance of unsafe failure modes (this is not the same as fail-safe), and the selective use of off-the-shelf equipment and hardware were guiding principles. Conventional traffic signal equipment and controllers were used at all intersections. Special lenses were used in regular signal heads where necessary. Consequently most spare parts can be obtained from the city or county traffic maintenance inventory.

Where LRT operates in a traffic environment, the LRT signals at intersections are generally visible to motorists. Because the LRT signals often indicate a movement in conflict with traffic, it was very important that the LRT signals not confuse drivers. In particular it was felt that red/green signals should be avoided, even with special shapes, because a driver with less than perfect vision may not readily distinguish a blurred T or arrow signal from a round one. Signage to indicate special meanings is not reliably obeyed and should be avoided where possible. Programmed visibility heads can get out of adjustment, resulting in confusion. Therefore white bar signals, which are meaningless to motorists, were adopted. The LRT proceed signal is a vertical white bar; the LRT stop signal is a horizontal white bar. The horizontal bar was later converted to yellow to assist train operators. The use of colors that do not trigger a reaction by motorists was considered an important safety consideration and also obviates the need for special signage to indicate the function of the LRT signals to the public. To provide the equivalent of a yellow phase, the bar signals flash for a set period of 5 sec before changing. This not only provides LRT operator reaction time, but also helps operators identify their signal in a sometimes brightly lit street environment.

Failure Control

One of the concerns throughout the design period was how the LRT system could continue to operate safely in the event of a traffic signal failure at a particular intersection. Sometimes dubbed, "how it works when it doesn't work," the concept was that failure of a loop detector to detect a train or failure of individual traffic signals or controllers should not significantly delay LRT operation.

At most regular intersections this is readily accomplished by operating rule without need for additional hardware. Typically the train, on not receiving the preempt signal as it approaches the intersection, would slow down and stop. Having stopped, the train may then proceed when conditions are safe. A safe condition typically occurs when the parallel pedestrian signal is lit, or when parallel traffic is proceeding and the left turn signals are red. Because the train operator can see the traffic signals, this backup mode does not require additional hardware. At a few locations (for instance, where a train is turning in an intersection), there may be no safe phase. At these locations a backup is necessary and is typically provided by installing a pedestrian push-button within reach of the train operator's window on the approach to such intersections.

Control Software

The primary traffic controller software was developed from a fully actuated intersection program that included a railroad preempt routine. This program was modified to accommodate a number of situations peculiar to LRT:

- The pedestrian clearance phase is not truncated by the train preempt. The practical consequence is that at a few locations where the train call loop could not be set far enough from the intersection, the train phase can be delayed a few seconds if the pedestrian phase is called just before the train phase.
- The preempt phase cannot be terminated without flashing for 5 sec. This provides enough time for a train to always clear the intersection, or stop before it, should the preempt end prematurely because of a false check-out call or erroneous timing.
- With the general adoption of right turn on red, the ability to control traffic turning right across LRT tracks is severely compromised. A number of solutions were considered, including use of changeable message signs and a general prohibition of such turns at all times. The control method selected is actually a composite, including a supplementary, train-actuated warning signal. This signal consists of a pedestrian signal head in which is installed the word Train. This signal supplements a permanent no turn on red restriction, so that when the preempt phase is actuated the signal flashes. This causes motorists to either search for the train or direct more attention to the traffic signal so that they will notice the no

turn on red restriction. This system is clear, simple, and has worked well.

DESCRIPTION OF ALIGNMENT

The Banfield light rail line extends from downtown Portland to the suburb of Gresham, a distance of some 15 mi. It has 9 crossings equipped with railroad gates, 55 intersections controlled by traffic signals, 7 controlled by stop signs, and 13 pedestrian-only crossings. The line may be divided into five segments that reflect different types of right-of-way (ROW):

1. Gresham segment, constructed on an old rail ROW,
2. Burnside Street, constructed on a suburban street median,
3. Banfield segment, a grade-separated segment beside a freeway,
4. Holladay, constructed in the city street, and
5. Downtown, where a variety of in-street configurations are used.

Gresham Segment

The outermost 2 mi of the LRT line was built in a abandoned Portland Traction Company ROW. Most of this segment operates on single track, with passing tracks at two of the three stations. The rail alignment on this segment is not tied to the local street system, which it crosses at locations independent of street intersections. There are nine at-grade street crossings on this segment. With this type of alignment configuration, grade crossings come under OPUC jurisdiction. Traffic signals were considered insufficient to provide adequate grade-crossing control, and railroad-style gates were installed, actuated by track circuits. These gated crossings are identical to similar crossings used statewide on the railroads, except that OPUC allowed the mandatory warning bell on the gates to cut out once the gates are in the down position—a concession to persons living in the vicinity.

Tri-Met operates about 170 trains daily through these crossings, which carry cross traffic up to 20,000 average daily traffic (ADT). No train/vehicular collisions have occurred at the gated crossings during the past 5 years, but gate arm replacement and vandalism repairs result in significantly greater maintenance than at the signalized crossings.

Burnside Street

The Burnside segment runs for approximately 5 mi in the median of Burnside Street. For about a mile of this length Burnside is a major arterial street with four heavily used traffic lanes. For the balance Burnside functions as a minor neighborhood collector street with a single traffic lane in each direction. The reconstruction of this street for LRT required widening the former two-lane street and installing a median, bike lanes, and turn lanes at intersections. Numerous residential and commercial driveways were reconstructed. Except at intersections, the new street fitted into the available 100-ft ROW. Many minor cross streets were closed at the median, so that they now accommodate only right in-right out traffic.

Seventeen traffic signal-controlled intersections were constructed at which traffic could cross the LRT tracks and make left and U-turns across the tracks. Figure 1 shows a typical Burnside intersection. The traffic signals at all 17 intersections are fully preempted by the LRT. The eight stations, all of them at intersections, all have farside platforms for several reasons. They result in the least traffic delay (because the train arrival time can be closely predicted from the upstream detectors) and thus minimize the preempt duration. Also the station geometrics allow the platforms to balance the left turn pockets, giving a uniform ROW requirement. And, should a train overrun a platform, it does not enter a crossing.

Train operation on Burnside is restricted to 35 mph, the same speed as the parallel traffic. Trains are operated on sight, without block signals or track circuits. The only signals are the preempt signals at the intersections. Preemption is initiated by the train passing over an inductive loop detector installed on the track that requests the traffic signal controller to go to the LRT preempt routine. The traffic signal controller, depending on where it is in the cycle, selects a clearance phase and then goes to the preempt routine. The distance from the call detector to the intersection is such that the preempt phase is timed to start before the train is within stopping distance of the intersection. If the preempt phase has not occurred by the time the train has reached stopping distance from the intersection, the train then stops at the intersection using normal service braking rates. Thus failure of a preempt is not an emergency condition. To define the

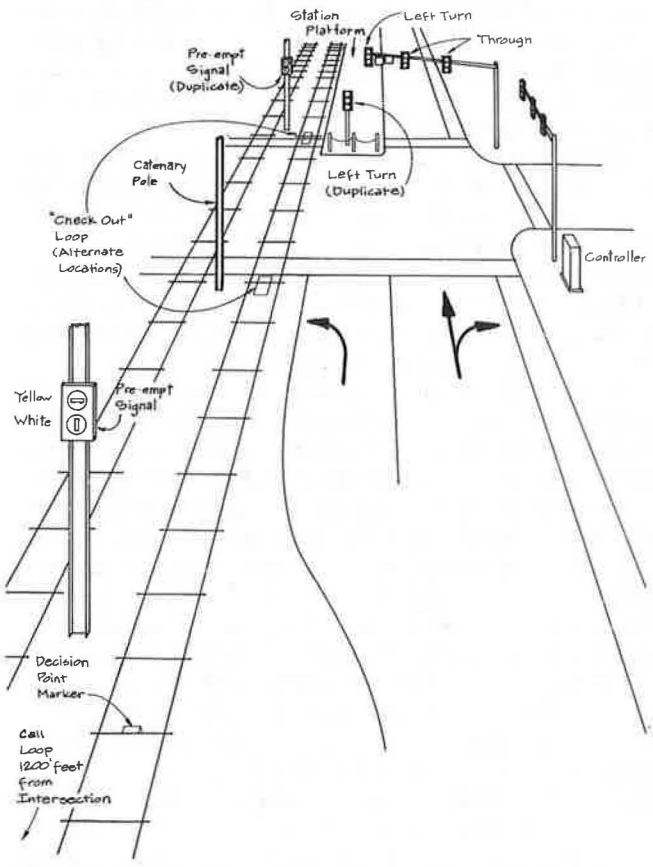

FIGURE 1 Typical Burnside traffic signal layout (half width of street).

point where the train operator should expect to see the preempt signal or begin braking, a reflective marker known as a decision point marker is installed in the track. An operating rule requires that if the preempt is not lit when the train reaches the decision point, the operator must apply the brakes. This process merely formalizes the process that all motorists use when judging stopping distance on the approach to a traffic signal.

All of the Burnside intersections are controlled by standard 170 controllers using a program customized for LRT operation. One of the features of this software is to warn the LRT operator before the preempt signal can change. The preempt signal normally rests with the horizontal bar lit, which is the LRT stop indication. If the preempt is proceeding normally this horizontal bar will flash for 5 sec before changing, thus giving the operator additional warning, and widening the decision window to approximately 7 sec in advance of the decision point marker. Similarly the preempt phase cannot revert to the stop phase without flashing for 5 sec. Thus if the preempt should accidentally terminate because of false checkout or another reason just as a train is approaching an intersection, there is no condition under which the train could enter the intersection against a signal once it has passed the decision point marker. The 5-sec flash interval, plus the 3-sec yellow and 1-sec all-red, provides enough time for the train to proceed from the decision point marker into the intersection in the available 9 sec. Once a train has passed the decision point marker, provided it is traveling at normal speed, there is no situation in which the traffic signal could change against it and allow a conflicting movement before the train has entered the intersection. Obviously if the train is traveling at less than normal speed, it can readily stop if the preempt should terminate early.

The Burnside preempt system achieves three important design goals:

- It is simple, using standard traffic signal hardware that can be maintained by the local traffic jurisdiction technicians and for which spare parts are readily obtainable. Other than the bar signal lenses for LRT and the track loops, no special parts or signs are needed.
- If the system fails to operate as intended, it creates no unsafe condition and does not require trains to make an emergency stop.
- Failure of a traffic signal or preempt does not result in delay to LRT operations of more than a signal cycle.

In addition to the signalized vehicular intersections, 13 pedestrian crossings allow pedestrians to cross the street and LRT tracks at locations remote from an intersection. These crossings are all unsignalized and have a Z-configuration, as shown in Figure 2. This simple design is found widely on European LRT systems. It provides a level, paved crossing with pedestrian refuge between the traffic and LRT lanes. It forces pedestrians crossing the street to turn towards a possible oncoming train on the adjacent track before they can cross the tracks. It enables pedestrians to cross the street without requiring a traffic-free condition across the entire street. As an additional safety precaution, LRT operators normally slow down if pedestrians are observed waiting in the Z-crossing refuges.

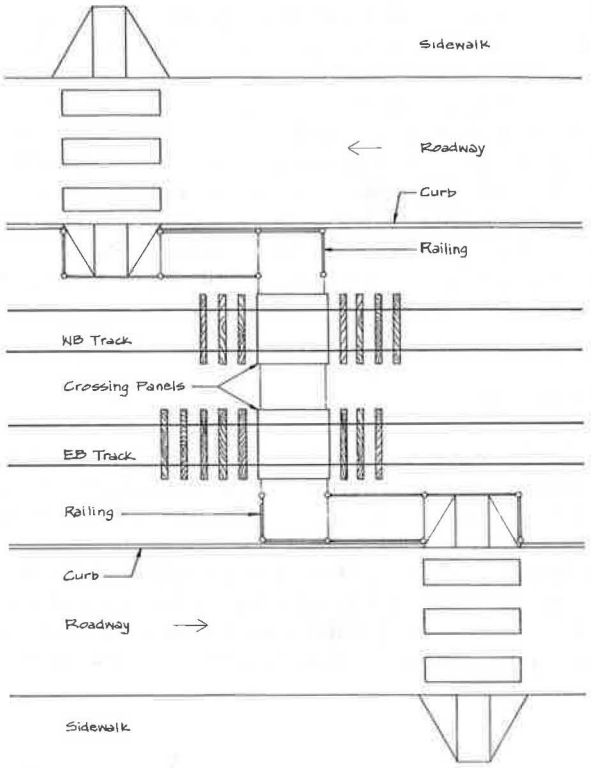

FIGURE 2 Typical Z crossing.

One of the Z-crossings serves as an access to a primary school and was a major concern to parents before operations started. The student-staffed crossing patrol that controlled the pre-LRT crosswalk now patrols the Z-crossing. If a train is sighted, the patrol retires to the sidewalk. If a train operator sees the patrol in the crossing the train will stop. This operation has worked smoothly ever since the LRT opened.

During the design of the Burnside segment the issue of fencing the median ROW was widely debated with the community. Ultimately the ROW was not fenced, although TriMet agreed to revisit the issue after operation began if the community requested.

Banfield Segment

At the west end of Burnside, the LRT turns out of the median, enters a short stretch of private ROW, and arrives at Gateway Station. Gateway Station is the midpoint of the line and a major transfer point for 12 connecting bus routes. The station is laid out with the bus bays forming a circle around the LRT station. This allows cross-platform transfers between bus and rail without any vertical separation. By constructing this station at grade the modal advantages of LRT are used to maximum effect. With no grade separation, the need for elevators or escalators is eliminated, and passenger transfers become faster and less onerous. For some transfers the distance between buses and trains is as little as 15 ft. Although the at-grade design results in slightly slower bus and train speeds, this is more than compensated by the reduction in both real and perceived travel time.

Continuing westward, the LRT line parallels the Banfield Freeway for approximately 5 mi. Apart from Gateway Station, this section is fully grade-separated with three intermediate stations accessed from bridge structures. At two of these stations bus pull-outs are provided on the bridges over the LRT. At the third a small transfer area is provided beside the LRT ROW. Maximum operating speed is 55 mph, and trains are protected by automatic block signals. Ironically this grade-separated segment has been the scene of the only fatalities on the system, all involving pedestrians trespassing on the ROW.

Holladay Street

The LRT leaves the Banfield Freeway and enters the downtown street system on Holladay Street, which it follows for approximately half a mile. Figure 3 shows the layout of the Holladay and downtown segments.

Holladay Street was formerly a minor arterial street carrying one-way westbound traffic from the Banfield Freeway to downtown Portland and the eastside commercial district. Because it was a one-way street, the LRT was constructed on the side of the street. On Holladay Street the LRT tracks are constructed on the north (right) side of the traffic lanes, within an 80-ft ROW, providing two traffic lanes beside the LRT tracks, one-way westbound. Although, in normal design practice, locating the tracks on the south side of this street would have been preferable (so that opposing directions would have passed on the right), this design was selected to place the Lloyd Center Station on the same side of the street as the shopping center of the same name, and because there were more numerous commercial driveways on the south side of the street. One significant traffic consequence was the need to control right turns across the tracks.

Throughout this segment the LRT tracks are constructed with girder rail, paved with concrete, and separated from the traffic lanes by a raised curb or planter. Sidewalks are on both sides of the street, with the north sidewalk between the tracks and the north edge of the ROW. Intermittent plantings are used along the LRT side of this sidewalk to channel pedestrians away from the trackway.

The 11 signalized intersections on this segment were designed to work within the preexisting westbound traffic signal progression, which in turn was tied to a north-south progression at certain intersecting streets. Westbound LRT trains

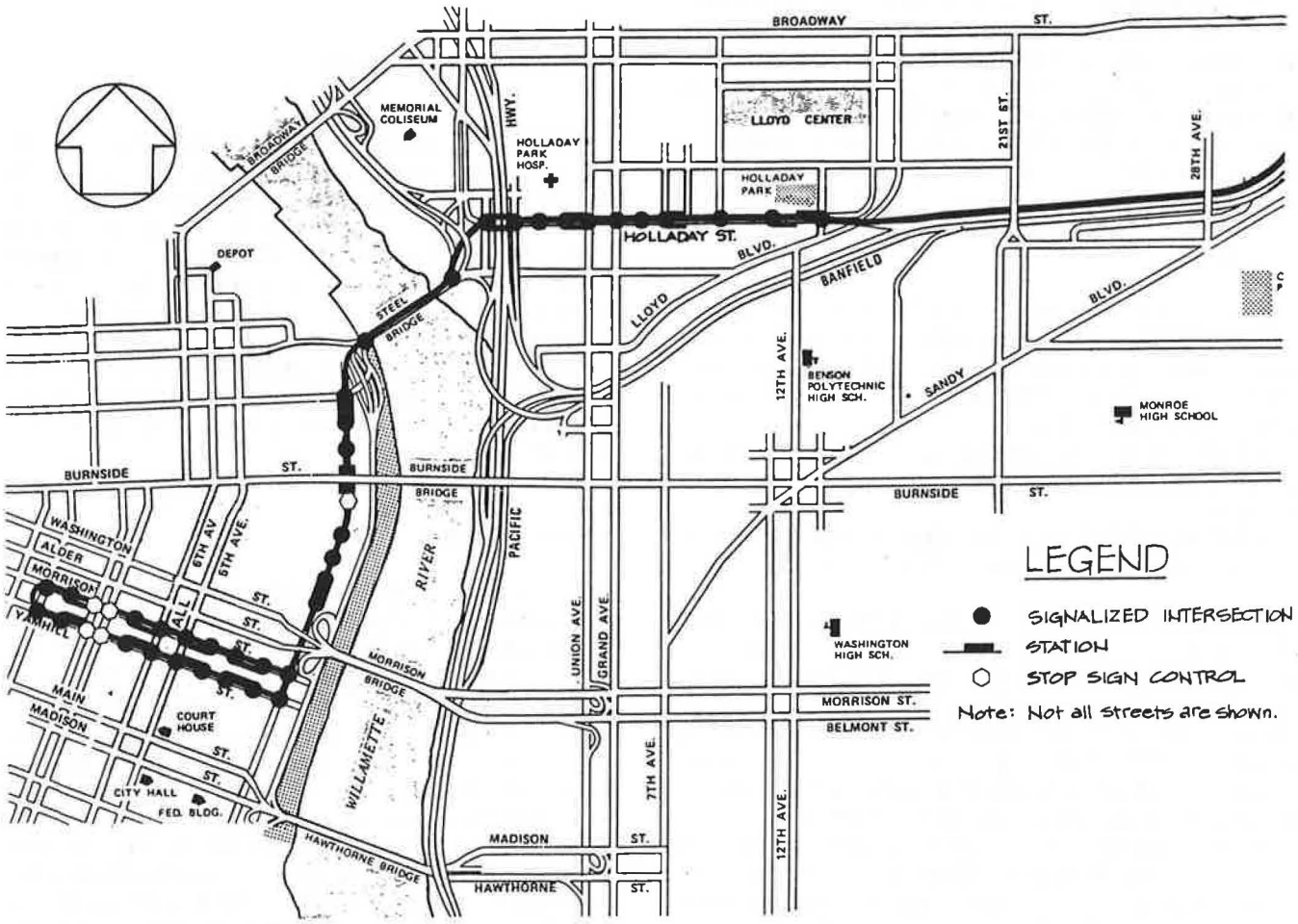

FIGURE 3 Holladay Street downtown layout.

would leave one of the two stations on this segment on a green signal and follow that progression to the next station. Because there was no eastbound progression, eastbound trains would call for a preempt (using a pushbutton at one location and a detector loop at the other) to set up an eastbound path that preempted alternate intersections to give a stop-free trip to the next station. This operation was complicated by one cross street that carried 21,500 ADT and that was not preempted in the original design. To provide a stop-free train path from station to station this nonpreempted street restricted train movents to one part of the signal cycle. The net effect of the Holladay Street design was that westbound trains had no effect on cross traffic, and eastbound trains had an impact only on alternate cross streets.

The control of right turn traffic across the tracks was a major issue on Holladay Street, and several designs were considered, including changeable message signs and turn prohibitions. In the design that was adopted, right turns were controlled by signs prohibiting right turns on red. These signs were reinforced by two flashing Train signs at each intersection. These flashing signs consisted of conventional pedestrian signal heads with the word Train used in place of the conventional pedestrian messages. Whenever the LRT preempt signal was lit, Train would flash, thus reinforcing the right turn on red prohibition.

Largely as a result of the unforeseen effects of LRT, Holladay Street has undergone significant change since the construction of the LRT. First of all, the construction of the LRT closed the street for more than a year with traffic detoured to other routes. As a result, when the street was reopened, much of the traffic that had once used it had found alternative routes and did not need to return. The delays to the parallel traffic progression caused by the all-red LRT preempts further discouraged traffic from returning to its former level.

The presence of LRT was a major factor in selecting a site on Holladay Street for the new Oregon Convention Center and development of a new traffic circulation plan for the area. One facet of this plan was the reversal of traffic direction on Holladay Street and its reduction to one lane with left turn pockets. This had the unintended effect of putting the LRT on the left side of the traffic flow instead of the right, thus removing the right turn on red problem, and making the former traffic signal progression irrelevant. Thus today Holladay Street has become a local circulation street, and the LRT now operates with full preemption in both directions. Traffic turns left across the tracks instead of right, protected by a left turn phase, so that parallel traffic can move on the same phase as the LRT.

Downtown Portland

Downtown Portland is separated from Holladay Street by the Willamette River, a major navigable waterway. To avoid constructing a new bridge, the LRT crosses the Willamette River by sharing an existing bridge (known as the Steel Bridge) with traffic. This 80-year-old structure has two decks, the lower deck carrying two railroad tracks, the upper carrying four highway lanes. Both decks have vertical lift spans in midriver to allow ocean-going ships to pass. The LRT tracks occupy the two center lanes of the upper deck of the bridge, sharing these lanes with highway traffic just as the streetcars did when the bridge was originally constructed. Sharing traffic lanes across the bridge requires a technique to merge a 200-ft train into a traffic lane at the approach to the bridge and to diverge at the opposite end. The approach merges are accomplished by train-actuated traffic signals in a similar manner to a metered freeway ramp. Normally traffic has uninterrupted access onto the bridge. When a train is detected, traffic is stopped until the train has cleared the merge point, after which traffic flow can resume, following the train onto the bridge. No active control is needed at the diverge point, which is indicated by signs and pavement markings.

The traffic signals at the Steel Bridge are overlaid by a track circuit-controlled interlocking that protects the lift span of the bridge. The bridge cannot be raised when a train is occupying the bridge, nor can a train enter the bridge approach track circuit when the bridge is raised. When the bridge is raised, trains are held at the nearest station on the approach side. Unlike the traffic signals, the bridge signals are enforced by the automatic train stop.

At the west end of the bridge, the LRT descends a 7.5 percent grade, the steepest on the system, into the downtown street network.

The downtown segment is some 1.5 mi in length, all of it in city streets. The line first runs south on First Avenue and then turns west onto a 10-block loop on Morrison and Yamhill streets. This segment passes through the retail center of the city and intersects the bus mall—two streets used by most of the regional bus service. All of the trackway is paved and is separated from traffic by contrasting paving and a rumble strip. Curb protection of the trackway in downtown is not practical because the narrow traffic lanes require that traffic be able to use the trackway to bypass obstructions in the traffic lane.

Because of the small size of the downtown blocks (200 ft) and the one-way street grid, the traffic can move within a signal progression in all four directions. The progression speed varies by time of day and is adjusted by changing the cycle lengths. The LRT was inserted into this system using the existing signal progression wherever possible to minimize the effect on cross traffic.

On First Avenue the LRT operates in two directions, although the traffic signals were set up for a southbound progression. Because First Avenue is only one block from the river, the main traffic streets pass over it on the approach spans to the river bridges. Consequently no major street crosses First Avenue at grade. As originally designed, southbound trains waited for the existing progression at each of the three stations on First Avenue and then ran with the progression to the next station. Northbound trains also waited for a green at each station and then could obtain a northbound progression by preempting alternate intersections. Thus the original design goal of stopping only at stations could be achieved.

Morrison and Yamhill streets have 60-ft ROW. LRT operates on the left side of the street in the same direction as a single lane of traffic and is tied into the signal progressions. Morrison and Yamhill streets cross all of the major north/south streets and the transit malls. By operating LRT within the existing progressions, traffic on the cross streets is largely unaffected.

VETAG

In 1990 two stations were added, one on Holladay to serve the new Oregon Convention Center and one downtown to serve a new retail development. These stations added more than 2 min to the LRT schedule, and a number of options were explored to compensate for the added dwell time. It was found that if the delays caused by waiting for progressions on Holladay Street and First Avenue could be eliminated, the 2 min could be recovered. However, this required the ability to preempt a traffic signal from a stationary train, a capability the system did not possess (except for the rather crude push-button system used as emergency backup at a few locations). After a study of system needs and available technology, a train-to-wayside communication system was defined that could not only preempt a traffic signal from a stationary train but also provide automatic track switch actuation and transmit train location to a central control. To fulfill this need, Tri-Met purchased the Philips Vetag system and installed it in 1989. Vetag is a loop- and transponder-based system originally developed in the Netherlands for bus and LRT preempt and switch actuation.

The initial Portland application was to enable stationary trains to call for preempts at stations on Holladay Street and downtown. This became possible because the city had determined that preempting signals on Holladay Street and First Avenue would not severely affect traffic and that the saving in train delays was a higher public priority. Vetag also provided the capability to retrofit Morrison Street to allow left turns across the tracks.

The Vetag installation was completed in 1990. A call button was installed on the control console of each rail vehicle, and Vetag loops and associated circuitry were installed at most of the downtown and Holladay stations. When a train pulls over the wayside loop, the call button in the cab is illuminated to inform the train operator that contact is established with the wayside. Preempt is called when the operator presses the call button. Because the preempt will not occur until the requisite intersection clearance intervals have elapsed, the train operator will call for preempt far enough ahead that the train is ready to leave by the time the doors are closed and the intersection has reached the preempt phase. The Tri-Met version of Vetag also allows the train to terminate the preempt phase by using the tail-end transponder to transmit a check-out signal. The experience with Vetag so far has been very satisfactory, and Tri-Met intends to expand its use as additional applications become necessary.

OPERATING EXPERIENCE

During the final stages of construction and preoperational testing, a number of potential problems were identified and fixes developed. Early in the project, tests were performed to compare overhead and buried loop detectors, resulting in the decision to use buried loop detectors. However when these loops were installed in the subballast they proved to be too deep to detect the trains. All of the loops installed under the initial Burnside contract had to be replaced with loops formed inside a fiberglass casing that could be bolted to track ties. These loops have provided highly reliable detection and in addition can be readily replaced should a defect develop.

In Oregon a single set of signal heads is normally used to control left turn movements. Although this arrangement is satisfactory in a normal intersection, it created an unforeseen problem at certain LRT intersections. In the event a single left turn signal loses a red light bulb or a programmed visibility head is knocked out of alignment, left turn traffic would see no signal. In this situation left turn traffic would normally proceed on the parallel green and expect to do so safely. However, with LRT operating parallel to traffic, the parallel green may also be the train phase, thus setting up a trap for the unwary. To guard against this situation a second set of left turn signal heads, at least one of which does not have programmed visibility heads, was installed at all intersections where this condition could occur.

The LRT trains are equipped with audible warning in the form of both bells and horns. The bells are used frequently in the downtown area as a method of alerting pedestrians in an inoffensive manner and to give routine signals prior to departing from a station and on similar occasions. The train horn is used primarily to warn traffic or to alert a pedestrian who has not responded to the bell. As initially installed, the horn sounded similar to an automobile horn with unintended negative consequence. When the train operator used the horn to warn traffic, traffic would sometimes believe that the driver behind them was impatient and they would therefore move ahead. Where the traffic happened to be turning traffic waiting for a train, this was exactly what was not desired. After a review of options, a new electronic horn was installed that could simulate a railroad locomotive horn. This appears to have solved the problem. The electronic horn has an additional advantage—both the notes and the intensity can be varied by the train operator to suit a particular situation.

Safe operation of the LRT system and particularly the traffic interface elements of that system has been a major concern throughout its development and early years of operation. Tri-Met's safety supervisor maintains a program of continuous review of LRT safety, including investigation of all accidents and incidents, and the compilation and review of all accident and incident information. One consequence has been the early identification of any location exhibiting unusual safety problems so that remedial measures can be investigated and implemented. For example, the high incidence of vehicles making an illegal left turn on Morrison Street and hitting a train was a major consideration in deciding to change the signal system to allow these turns. A high incidence of right turn on red accidents at 13th and Holladay was reduced by rearranging the signals, signs, and flashing train signs at that location.

Table 1 summarizes Tri-Met's accident experience in its 5 years of operation. During this period the rate of bus accidents has tended to rise, whereas the rate of rail accidents has tended to fall, with the modes currently experiencing very similar rates measured on a vehicle mile basis. Because of the greater ridership on the rail vehicles, the accident rate per passenger mile is between five and six times lower on the rail system.

Although engineering efforts have provided a foundation for safe operation, even more effective has been the defensive driving skills developed by the operators, who have learned to recognize potentially hazardous situations and have de-

TABLE 1 Summary of Transit Vehicle Accidents by Mode

	Bus	Rail
FY-87		
# Vehicle Accidents	791	45
# Vehicle Miles	21,020,000	700,000
# Passenger Miles	158,093,540	36,394,000
Passenger Miles/Vehicle Accidents	199,865	808,755
Vehicle Miles/Vehicle Accidents	26,573	15,555
FY-88		
# Vehicle Accidents	830	43
# Vehicle Miles	20,970,240	840,720
# Passenger Miles	136,663,200	38,214,000
Passenger Miles/Vehicle Accidents	164,654	888,697
Vehicle Miles/Vehicle Accidents	25,265	19,551
FY-89		
# Vehicle Accidents	776	54
# Vehicle Miles	20,935,200	842,760
# Passenger Miles	144,460,800	36,888,000
Passenger Miles/Vehicle Accidents	186,160	683,111
Vehicle Miles/Vehicle Accidents	26,978	15,606
FY-90		
# Vehicle Accidents	833	38
# Vehicle Miles	21,075,120	852,600
# Passenger Miles	159,188,658	37,981,091
Passenger Miles/Vehicle Accidents	191,102	999,502
Vehicle Miles/Vehicle Accidents	25,300	22,436
FY-91		
# Vehicle Accidents	984	41
# Vehicle Miles	21,467,040	852,000
# Passenger Miles	168,696,000	42,036,000
Passenger Miles/Vehicle Accidents	171,439	1,025,268
Vehicle Miles/Vehicle Accidents	21,816	20,780

veloped responses. Many tactics have been incorporated into the driver training program to good effect.

CONCLUSIONS

In 1986 Tri-Met opened a new LRT system with some 71 grade crossings in 15 mi, and an ROW extending from the city center to the outer suburbs. It has proved that LRT can be safely and reliably operated in a major urban area and has led to public endorsement of the eventual construction of a regional rail system. The future extensions will generally follow and build on the experience from the initial line:

- Use conventional traffic control and railroad devices, intersection configurations, and hardware to benefit from existing public familiarity and simplify design and maintainability.
- Do not provide motorists with information they do not need. Particularly do not display the train signals to motorists and then have to install signs to tell drivers to ignore the signals.
- Try not to prohibit normal traffic moves to avoid having to control them. A percentage of traffic will typically not observe the prohibition and an unsafe situation can develop. Observance of signals that permit and control movements is safer and more predictable.
- Construction of LRT requires extended street closures and forces changes to traffic flow patterns. Opportunities often exist to use this disturbance to manage traffic flow after construction and create an enhanced urban environment.