Overview of Light-Rail Train Control Technologies

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The various modes of operation of current U.S. light-rail transit (LRT) systems, the limitations of conventional train control technologies, and the capabilities and basic components of more advanced and emerging technologies are described. The operational constraints experienced by some LRT operators as well as the progress in applications of advanced control and communication technologies are also discussed.

Light-rail transit (LRT) systems have been enjoying growing popularity because they are considered socially and environmentally attractive and often incur lower operating costs compared with other transit modes while providing medium capacities [2,000 to 25,000 persons per hour per day (pphpd)]. Most of the 18 transit agencies operating LRT systems in the United States are planning to expand their systems. LRT is also being considered by many cities that do not have the size and density to justify conventional heavy-rail systems.

Despite the advantages offered by LRT, many systems have been experiencing problems related to safety and capacity. Many systems have reached or are anticipated to reach full capacity because of rising ridership. Increasing the capacity beyond the design limit is, however, not easily achieved because of, for example, speed constraints imposed by track geometry, outdated equipment conditions, or mixed traffic operations.

To alleviate the aforementioned problems, new technologies are needed that offer a cost-effective way to ensure safety and add system capacity without requiring significant investments in infrastructure. Avanced train control and communications technologies form one group of such technologies. Transit authorities in North America, such as the San Francisco Municipal Railway (MUNI), Los Angeles County Metropolitan Transit Authority (LACMTA), Metropolitan Transportation Authority New York City Transit (MTA New York City Transit), Toronto Transit, Southeastern Pennsylvania Transportation Authority (SEPTA), Metropolitan Boston Transit Authority (MBTA), and others, are investigating and evaluating alternative train control and communications technologies. The major incentives to upgrading or replacing the existing control and communications systems are increased safety, higher reliability, and greater operational flexibility compared with the existing fixed-block and wayside technologies.

According to a 1992 report prepared by the Office of Policy under the Federal Transit Administration (*1*), approximately $1.52 billion was spent between 1983 and 1991 on "improvements" to U.S. rail transit systemwide control components including signals, cables, relays, and other equipment necessary to provide control, communication, and supervisory functions. A before-and-after assessment showed that although there were some improvements to control systems that were considered in excellent condition, there was considerable deterioration in the control systems that were assessed to be in good, fair, or poor condition. As a result, the percentage of control systems in good condition decreased from 54 to 33 percent, resulting in an increase in the number of control systems in fair or poor condition (from 28 to 46 percent). The number of communications and supervisory-and-control systems in fair or poor condition increased from 63 to 82 percent and from 20 to 30 percent, respectively. It was concluded that most deterioration in condition occurred in light-rail vehicles (LRVs). The outdated condition of the current light-rail control systems coincided with the 59.5 percent increase in the LRT operating expenses during the period between 1984 and 1993, a substantial increase compared with the 33.6 percent increase in operating expenses for bus transit and 29.3 percent for heavy-rail transit (2).

Selection of equipment has proved a difficult decision because of the lack of performance and communication standards for specifying guideway transit equipment. Much time and money have been spent by both transit operators and suppliers to find new technologies with a high degree of interchangeability and the capability of being overlaid on existing technologies. In this paper, operating modes of current LRT systems, the operational constraints experienced by LRT operators, and the limitations of conventional train control technologies are discussed. The capabilities and components of more advanced and emerging control and communication technologies, and the progress in their applications are also reported.

EXISTING LRT CONTROL TECHNOLOGIES

Table 1 provides a summary of the current control systems and some operating statistics for 16 LRT systems in 15 U.S. cities. It may be seen that even when highly sophisticated electronic control systems are available in today's market, the majority of the LRT systems in the United States are still manually operated, sometimes with the "improved and safe" speed control system. Both operating modes described in this section, manual train operation and manual train operation with speed control, incur large costs for operation, maintenance, repair, and equipment replacement.

Manual Train Operation

Manual train operation relies completely on the operator and the operator's experience and judgment in obeying the signals. It requires the driver to respect wayside speed and light signals. One of the major problems with this mode is the high maintenance and replacement costs for equipment and labor. In addition, the train driver does not have a way of determining train berthing, speed of the lead train, and station dwell time.

Manual Train Operation with Speed Control

In manual train operation with speed control the train driver also has full control of the train, but the speed is automatically supervised and constantly displayed to the driver by the automatic speed regulation (ASR) system. ASR is accomplished with fixed-block and wayside equipment that transmits the speed command that is prewired for each track section to the onboard equipment. The fixed-block technology, having been proved over several years, requires the installation of track circuits and offers speed control and stop protection on the line. Speed command selection depends on the number of clear blocks ahead and is calculated on the basis of interlocking information, traffic, train location, speed rating, and braking potential. This operating mode is most commonly used in U.S. LRT systems. The major drawback of this operating mode is the lack of long-term reliability of mechanical relays, the need for recalibration every 5 years, and the performance limitations of the equipment.

OPERATING CONSTRAINTS EXPERIENCED BY LRT OPERATORS

In this section the operating constraints experienced by four LRT operators are described. The information was obtained from reports, interviews with personnel from the transit agencies, and from authors' observations.

San Francisco Municipal Railway

MUNI trains are manually driven with speed control. LRVs operate in the subway under the train operator's control with cab signal supervision. The train driver controls the doors, platform berthing, direction, coupling and uncoupling, onboard announcements, and radio communications to the central control. Train dispatching is managed by supervisory personnel at trackside in communication with central control.

A conventional railroad-type signal system provides interlocking control, wayside route indications, and manual cab signals. Over-speed protection is provided for only three speeds: 16, 32, and 43 km/hr (10, 20, and 27 mph). In the normal direction of travel, wayside signals approach clear, but the central control has the ability to manually operate the five subway interlockings during emergencies with an overlaid centralized traffic control system.

In the subway, train direction and movement below 16 km/hr (10 mph) are not restricted by the signal system. There is no zero-speed command, cab signal stop indication, or wayside trip-stop system. LRVs are

TABLE 1 Operational Characteristics of Selected LRT Systems (2)

Cities	Minimum Headway (minutes)		Average Operating Speed (km/h)*	Train Control System	Operating Expenses/ Veh. Rev. Km[c] (1993$)	Operating Expense/ Pass-Km[c] (1993 $)	Unlinked Pass-Trip/ Veh. Rev. Km[c]
	Designed	Operated					
Los Angeles							
Blue-Line[a]	3	6	34	M, ATP	9.50	0.25	2.56
Green-Line[b]	2	5	n/a	ATC	---	---	---
Portland	3	3	31	M, ASC	4.83	0.42	3.21
Baltimore[a]	15	15	n/a	M, ASC	6.32	0.32	1.76
Buffalo	2	5	19	M, ASC	8.82	0.41	5.64
Denver	n/a	5	48	M, ASC	---	---	---
Sacramento	15	15	34	M	5.80	0.30	2.44
San Diego	2.5	4.25	20	M	2.80	0.11	2.31
St. Louis	5	7.5	48	M, ASC	---	---	---
Boston[a]	n/a	7.5	21	M, ASC	11.20	0.43	11.45
New Jersey	n/a	2	29	M, ASC	4.62	0.32	2.88
Philadelphia[a]	n/a	3	32	M	8.33	0.27	8.22
San Fran.[a]	2.5	10	18	M, ASC	10.11	0.37	6.30
Cleveland	2	6	29	M, ASC	6.93	0.25	2.63
Pittsburgh	3	3	23	M	8.35	0.42	2.69
San Jose	n/a	10	32	M	7.06	0.29	2.25

Notes:	*M*	*Manual Operation*
	ATC	*Automatic Train Control*
	ATP	*Automatic Train Protection*
	ASC	*Automatic Speed Control*
	[a]	*Systems considering advanced train control systems*
	[b]	*Systems considering fully automated control system*
	[c]	*To obtain MPH and/or Veh. Rev-Mile multiply by 1.61*

equipped with deadman control, spin-slide control, blended friction and dynamic grid disk brakes, electric track brakes, and sanders.

For MUNI, three major constraints limit the system's capacity and the ability to maintain schedule adherence: the terrain, aging signal control and vehicle equipment, and transitions between surface and subway operations. The specific problems include the following (*3*):

- Collision avoidance in the subway when speed is below 16 km/hr (10 mph) relies on the train operator's adherence to rules and use of good judgment;
- The design characteristics of the existing over-speed protection system, combined with few speed commands and the steep grades, frequently result in unnecessary emergency brake applications when trains are operating at the maximum commanded speed; and
- Since the signal system has a limited fault tolerance, virtually any failure dramatically reduces system performance.

SEPTA Light-Rail System

The SEPTA system consists of three currently inactive surface lines and five subway-surface lines. Each track of the double-track system is signalized for unidirectional movements. There are neither passing sidings nor crossovers between the two main tracks. Slowing or stopping of traffic at any point inside the tunnel, especially during peak periods, has a ripple effect on the rest of the traffic as well as on overall vehicle flow within the tunnel. The existing signal system consists of three types of signals (*4*):

- Automatic block signals: These provide conventional two-block, three-aspect protection (red, yellow, and green), which governs the entry into a typical signal block.
- Speed control signals: These are electrically timed and are actuated on the approach to a signal. The function of these signals is to restrict speeds for curve and grade conditions or to maintain a reduced speed through several consecutive blocks. The signals require the vehicle operator to reduce speed until the signal displays a more favorable indication. These speed control signals are used to increase the safety level but tend to cause an overall decrease in operating speed.
- Call-on signals: These are primarily used for vehicles entering a station to allow more than one vehicle to berth at that station platform. This is accomplished by dividing the platform track into two track circuits, front and rear.

SEPTA has experienced the following problems:

- Minimum scheduled headways on some routes are 3 min and 30 sec in the tunnel, and cannot be decreased further. The present line capacity during peak periods with 50 to 60 cars per hour has reached its limit for safe operation in the tunnel.
- During peak hours, the demand for service exceeds supply on certain routes. As a result of peak operating conditions, SEPTA is able neither to improve the schedules nor to inform the passengers of delays.
- The most serious deficiency of the existing signal system is the lack of speed enforcement. There are no onboard devices that will actuate automatically if the car operator ignores a wayside indication. The chances of human error in this situation are much higher than with an automatic system.
- There are no signals from 15th Street to 22nd Street except for clusters of short blocks in certain areas.
- The signal system in the tunnel reflects the operating demands and philosophy of the 1950s when a heavy concentration of vehicles operating on a close headway of 20 to 30 sec at slow speed was needed to carry passengers through the tunnel.
- Speed control signals were installed to improve safety following incidents such as derailments or rear-end collisions, which have further reduced operating speeds.

San Diego Trolley

The system is modeled after western European systems with a rolling stock that is composed of German type U2 articulated LRVs. Parts of the system operate on freight tracks. The San Diego Trolley is a manually driven system, with the operator controlling the vehicle speed and a dispatcher controlling the track switching. The system operates with rail switches and signal lights that have remained essentially unchanged from century-old railroad technologies.

The system is experiencing several problems (5):

- Operation of the San Diego Trolley in the downtown area is constrained by street block lengths that accommodate only two-car trains without overhang. During peak hours, however, four-car trains are needed. Although train length is reduced to three cars at the Imperial transfer station before the train enters the downtown, pedestrian traffic is still impeded at intersections in the downtown area.
- Traffic control signals in downtown are synchronized to allow the progression of LRVs through signalized crossings. This progression is accomplished only if the train operator leaves the station at the beginning of the green phase of the first intersection in downtown. At this intersection, there is a countdown device that informs the operator that the light will change in 15 sec. When the light turns green, the operator has to close the doors and be ready to start running the train to catch the "green wave."
- Ridership in the downtown area is increasing, but service frequency is limited to 90-sec headways to synchronize LRT system operation with the control signal.

Boston-MBTA Green Line

The Green Line system operates over 37 route-km (23 route-mi) that is a combination of exclusive right-of-way (ROW) (subway and elevated), reserved ROW that interfaces with traffic at street crossings, and mixed ROW. The system consists of four lines with 70 stations, four of which are connected with heavy-rail lines and one of which is connected with the commuter rail.

Three of the four lines operate with a 5-min peak headway, and the remaining line operates with an 8-min headway. The four lines pass through the 12.4-km (7.7-mi) Central Tunnel, which allows a minimum headway of 65 sec only during special events and 83 sec during regular peak hour operation.

There are two problem areas—traffic management and the signal control system (6):

- LRVs that interact with traffic operate with no special signal timing or signal preemption. Parts of the signal system in the private ROW predate World War II. Traffic engineers at MBTA are testing a device that detects a stopped train at an on-street station and turns the upstream signal red to alert automobile drivers not to pass the LRV and to allow the passengers to alight onto the street. This device provides only marginal safety for passengers and causes unacceptable congestion for street traffic.

- The system uses a type of automatic vehicle identification (AVI) that provides partial train supervision and route control. However, a train is identified only when it is passing a loop. There is no information about the train location between the loops. Communication with a train can be achieved only when it is over the loop and if the vehicle initiates the communication. If the vehicle fails to communicate, the control center will be unaware of the vehicle's current position.
- The system relies completely on the operator to obey the signals. Human error is the most prevalent cause of incidents and accidents.
- The system is supposed to operate with 83-sec headway, but because of vehicle bunching, the headways are less than 45 sec. Vehicle bunching causes all trains to make a mandatory stop before entering the North and Lechmere stations.

NEW TECHNOLOGIES IN LRT OPERATION

In recent years, new technologies in train control systems have been developed rapidly with the well-defined goals of increasing capacity, enhancing safety, and providing a high degree of interchangeability for mixed-mode operation. Table 2 describes the most important functions of different control technologies. In Table 3 information about North American train control equipment suppliers is provided.

Automatic Train Control Systems in Conjunction with Train Attendants

Automatic train control (ATC) system technology with train attendants is considered a mature technology since it has been used in heavy-rail system operation for many years with positive results to solve capacity and safety problems. Currently, ATC technology is considered the

TABLE 2 Functions and Capabilities of Train Control Technologies

	LRT Systems Control Technologies				
Operating Mode Functions	Manual with Wayside Signals	Wayside Fixed Block	Fixed Block & Cab-Signaling ATO, ATP	Comm-Based & ATO, ATP	Overlaid Comm-Based & ATO, ATP
Train detection	Limited	Yes	Yes	Yes	Yes
Safe train separation	Limited	Yes	Yes	Yes	Yes
Over speed protection	No	No	Yes	Yes	Yes
Broken rail detection	Limited	Limited	Limited	Limited	Limited
Minimize headway & max. throughput cap.	No	No	Limited	Yes	Yes
Centralized dispatching, identification & schedule adherence capability	Limited	Limited	Yes	Yes	Yes
Provides ATS	Limited	Limited	Yes	Yes	Yes
Interface with ROW intrusion detection	Limited	Yes	Yes	Yes	Yes
Public information on real-time basis	No	Limited	Yes	Yes	Yes
Ease of train operation	No	No	Yes	Yes	Yes
ATP compatibility	Limited	Limited	Yes	Yes	Yes
ATO compatibility	No	Limited	Yes	Yes	Yes
ATS compatibility	No	Limited	Limited	Yes	Yes

TABLE 3 Control and Communications Technology Suppliers in North America

Suppliers in North America	Type of Equipment Supplied										
	Mechanical	Electrical/ Electronic	Track Circuits	ATC & Train Stops	Multiplexing	Level crossings	Marshalling yards	Software	Cables/fiber optics	Automated transit	Lineside equip.
Amtech				✓							
CMW Systems		✓	✓	✓	✓	✓	✓	✓	✓		
Electro-Pneumatic Corp.		✓	✓			✓		✓			
General Railway Signal	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Harmone Industries		✓			✓						
Safetran Systems	✓	✓	✓	✓		✓					
Siemens Transp. Systems		✓	✓	✓			✓	✓		✓	✓
Transcontrol Corp.		✓	✓	✓		✓	✓				
Ultra Hydraulics							✓				
Union Switch & Signal	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Western-Cullen-Hayes	✓	✓				✓	✓				
ALCATEL, Canada		✓	✓	✓	✓	✓		✓	✓	✓	
GEC/ALSTHOM, Canada		✓	✓	✓	✓	✓		✓	✓	✓	

Source: Railway Directory, 1995

most suitable alternative to expand and upgrade LRT systems.

For a heavy-rail system with ATC, the train driver's functions are limited to providing information to passengers at stations, operating vehicle doors, and controlling the trains if the automatic system fails. In fact, the door operations could also be accomplished by ATC, but because of safety considerations, it remains a manual process. Trains are routed by signal indication, with continuous display in the cab to keep the train attendant informed of operating conditions. Vehicle operation is totally commanded from the control center. Control consoles in the center are used for the remote control and monitoring of all interlockings. The routes of individual trains may be monitored with reference to their train identification numbers.

An ATC signaling system interfaces with most vehicle functions, including traction motors, brakes, and public address systems. The three major subsystems of ATC are automatic train protection (ATP), automatic train operation (ATO), and automatic train supervision (ATS).

Automatic Train Protection

The train operator has command of the train operation, but his or her actions are supervised automatically in real time with data from the signals, blocks, and switches. The ATP system continuously checks that the train can proceed safely in reference to the next stopping or slowing point. The train operator receives an alarm whenever the authorized speed is violated, and a predetermined time is allowed for the operator to request a full-service brake rate before the ATP system invokes a full-service brake penalty to zero speed.

Automatic Train Operation

The decision about whether the train is to run under an automatic control system is made on the vehicle by the train operator. ATO provides the basic operating functions such as controlling the running and headways of trains, managing stops in stations, controlling the opening and closing of train doors, and providing audio and visual information to passengers. Generally, the fixed-block system concept is used for train separation.

Automatic Train Supervision

ATS functions include routing of trains, train dispatching, train tracking, adjustment of train performance levels, generation of alarms and indications for both vehicles and wayside, generation of operational and vehicle maintenance reports, control of station dwell times, and identification of trains. The ATS subsystem consists of a computer, console and displays, and a communications control center. The computer system's function is primarily to optimize operating efficiency. It controls and supervises departure times, routing, dwell times, and other corrective strategies. In addition, the computer monitors the operation of interfacing systems such as escalators, passenger gates, fans, vents, and the power distribution network. Through the control center, ATS monitors the position and adjusts the performance of all trains (7).

Although an ATC system is capable of operating trains without drivers, it does not have adequate safety features (see discussions on fully automated systems below) to allow the fully automated operations that make on-board drivers unnecessary. Because of the diverse LRT system operating environments, the presence of drivers is essential, and they may need to perform more functions than those that a heavy-rail train operator typically does. Using the ATC system for LRT operation in mixed ROW requires implementation of LRT-road interface management to control traffic signals at crossings. Infrared devices may be installed on the vehicles, which will preempt street traffic lights accordingly, giving priority to LRVs. This function may also be accomplished by using induction loops in the tracks or automated traffic surveillance and a control system that detects a train approaching an intersection and adjusts the signal progression to allow the train to pass through the next intersection without stopping.

Fully Automated System

With a fully automated control system, a train is operated automatically, including starting, stopping, driving, coupling, towing, and door opening and closing, eliminating human error in the operating process completely. No on-board drivers or attendants are necessary. All functions are integrated. For instance, ticket sales may control the traffic capacity and number of trains needed. A fully automated train control system includes the same functions as the ATC system but with added fail-safe measurements that permit the removal of on-board human drivers. For a fully automated system, ATP is the most important function, providing the basic safety operations, including safe spacing of trains, over-speed protection, switch controls and interlocks, and door control interlocks. ATO is responsible for vehicle speed regulations within the safe envelope set by the ATP subsystem, which also governs station stopping programming, vehicle and door timing control, and command coordination between stations and the central control. ATS operates within the constraints of the ATP system by means of an integrated set of equipment, which includes the central computer, train control and power distribution displays, control consoles, and communication equipment.

The complete system equipment for the control subsystems (ATP, ATO, and ATS) is located at the central computer complex, at the stations, along the guideway, and on board the vehicles. Interactions of the subsystem functions are very complex, and sophisticated interfaces are required between them. If there is a failure in the central system and no manual mode is available, the entire line will stop operating.

In addition to the complex equipment, a fully automated system requires 100 percent exclusive ROW, often resulting in a significant increase in the capital costs. The benefit, however, is a better level of service, including high speed, short headways, high reliability, and enhanced safety.

Communications-Based Technologies

The term *communications-based* refers to a train control system that uses an intensive two-way or bidirectional communication data link between the wayside and the train to detect continuously the position and speed of the train as well as the trains preceding and following it, allowing for decreased headways and increased throughput. The system is also called a transmission-based signaling (TBS) system or communications-based signaling (CBS) system. CBS does not require track circuit hardware. Instead, a wireless system is used to transmit information either from vehicle to vehicle or from vehicle to wayside or central office. It creates a phantom block or a shadow between the rear of a preceding train and the front of a following train. Depending upon how fast each train is moving, the size of the shadow can be changed, allowing the distances between train to vary for different types of trains operating at different speeds, hence the name *moving block*. At slow speeds, less space between trains is needed. At higher speeds, greater braking distance is required, thus a longer block. CBS is a proven technology over the last 12 years and has been applied primarily in Europe. As of 1996, it will also become available to the U.S. market.

In a CBS configuration, the train must determine its location on the wayside. Several technologies can be used for this function, including tachometers, radar, loop transposition detection, transponders, Global Positioning System (GPS), digital maps, and inertia measuring devices (gyroscopes and accelerometers). Once a vehicle determines its location on the wayside, it transmits its location back to the wayside via RF data radio or low-frequency inductive coupling. RF data radio is currently being explored by many companies (*8*).

Advanced Train Control Systems

An advanced train control system (ATCS) is a fault-tolerant, wireless train control system that utilizes microprocessors and digital data communications to connect elements of the railroad, vehicles, track forces, and wayside devices to the dispatcher's office. In addition, it will link data to key railroad managers through an information management system. The ATCS eliminates dependence on human compliance with signal indications, operating rules, and written instructions to achieve safe speeds and train separation. It allows increased traffic capacity and equipment utilization and maximizes electrical and labor savings.

Information management is one of the two principal functions of the ATCS: it issues work orders, monitors system health, calls crews, records events, and plans dispatching strategies. The other principal function is vital and nonvital train control: throwing switches, moving trains, and stopping trains. Some of the most important benefits of ATCS are as follows:

- Increasing traffic capacity on existing tracks by decreasing headways, mitigating the need for additional track;
- Decreasing the number of cars required for revenue operation by allowing trains to run faster; reduced trip times require fewer trains to maintain the same headway;
- Reducing brake rates, resulting in reductions of energy usage and trip times;
- Providing multiple-train coordination, decreasing peak power demand and the size of propulsion substations;
- Allowing easy installation and overlay on existing systems, permitting mixed operation modes; and
- Ensuring that all train movements are safe, valid, and observed, eliminating all possibility of human error.

Today, ATCS is considered the train control technology with the greatest potential to solve safety and capacity problems and at the same time offer savings on capital and operating costs.

Positive Train Control Systems

Positive train control (PTC) is the Federal Railroad Administration's term for what has previously been called positive train separation (PTS) to denote collision avoidance. PTC is a highly capable technology, not only for preventing train accidents and casualties, but also for preventing violation of permanent and temporary speed restrictions, including restrictions that protect on-track workers and their equipment.

When a CBS system is overlaid on an existing, vital traditional fixed-block system, it becomes a PTC system. The total safety of the combined system is enhanced as compared with the traditional signaling system. It is possible to develop PTC technology that provides varying levels of operation, depending on how much or how little of the current signal and control system is to be retained. A PTC system that is overlaid on an existing signal system and provides enforcement of occupancy and speed restrictions is called basic PTC. An enhanced PTC system is vital (with fail-safe characteristics) and is capable of replacing fixed-block signal systems.

PTC systems have the potential for improving the management of train operations in various ways and at lower costs than conventional ATC. With a PTC system, the brakes would be applied automatically, if necessary, to keep trains apart, enforce a permanent or temporary speed restrictions, or stop the train short of a switch not properly aligned for that train or other known obstructions such as on-track maintenance equipment (*8*).

Advanced Railroad Electronic Systems

The advanced railroad electronic system (ARES) was designed by Burlington Northern Railroad (BN). In conjunction with Rockwell International, BN implemented a test bed for ARES in Minnesota from 1988 through 1993. ARES is an integrated command, control, communications, and information system, designed to control rail traffic with a high degree of efficiency, precision, and safety. The data link uses the railroad's existing microwave and VHF radio frequencies to communicate information, instructions, and acknowledgment between the control center and a train or other track vehicles. To determine position and speed, ARES uses GPS to provide the control center with highly accurate three-dimensional vehicle position, velocity, and time data (*8*).

State-of-the-Art GPS-Based Control Technology

For service monitoring within noncommunicating territories, GPS may be used for a state-of-the-art LRT information management and control system using maps as a common reference frame. GPS is a satellite-based technology used to determine the position of a point anywhere on the earth's surface. Basically, a GPS-based control system includes two main components, a vehicle location and tracking system and a scheduling support system. Vehicle tracking is performed through a sequential polling process that provides automatic updates of vehicle location on the map display. These two components provide dispatchers with the necessary tools to make safer operating decisions and monitor operator or vehicle performance. Some important applications may be vehicle location, vehicle identification, passenger information, schedule adherence, and emergency response.

IMPLEMENTATION OF NEW TECHNOLOGIES

New Control Technology for MUNI Metro System

Operational studies and computer modeling performed by MUNI demonstrated that the capacity problems could be solved if (*3*)

- The time necessary to turn trains at Embarcadero Station was minimized,
- Limitations associated with the existing signaling system and LRV train reversal functions were mitigated, and
- All train movements in the subway were globally controlled, coordinated, and optimized.

MUNI determined that the technology had to have at least 2 years of proven applications and actual in-service use for a mass transit system in at least one city. Subsequently, an ATCS was determined to be the most suitable technology to mitigate the existing constraints.

The primary objectives for implementing the ATCS are

- Eliminating as much as possible manual operations and decisions;
- Improving safety by eliminating human error and equipment or system failures as potential causes for accidents and injuries;
- Increasing reliability and availability and lowering maintenance costs by replacing existing maintenance-intensive equipment with equivalent service-proven equipment that requires less maintenance;
- Allowing flexible operation to permit additional shuttle service and improve management and recovery in the event of equipment failures or other emergencies;
- Providing additional operational flexibility and fully automated control of new track area associated with the MUNI Metro Turnback, which is under construction;
- Enhancing passenger information systems and improving right-of-way security against intrusions;
- Providing capability for mixed-fleet and dual-mode operation and for future expansion projects; and
- Providing capability for 60 trains per hour per direction and the ability to control 40 trains at any one time.

The ATCS project funding information obtained from MUNI ATCS Systems Coordination Department (Patricia G. DeVlieg, project engineer) is given in Table 4.

TABLE 4 Funding for MUNI's New Control System

Category	Funding ($)
Project Management, Administration, Test & Start	4,963,250
Consultant Services	6,851,425
Construction Contract	52,725,465
Sales Tax	2,717,232
Contingency	1,221,710
Project Total	**68,479,082**

Improving SEPTA Light-Rail Control System

In addition to solving the capacity problem, the new technology was expected to satisfy the following criteria :

- It is a proven technology used on a transit property with demonstrated results;
- It has distinct advantages in terms of operations, control, and maintenance functions;
- It has sufficient redundancy to operate trains safely and efficiently under normal and contingency conditions;
- It offers all automatic train control features such as ATO, ATP, and ATS, while allowing manual operation;
- It allows mixed operation with the ability to enable communication between new and existing vehicles about their locations; and
- It is able to perform all existing functions such as call-on, multiple berthing at stations, civil speed restrictions, and interlocking operations.

After reviewing eight different systems (three fixed block and five moving block) offered by seven suppliers, SEPTA found that moving-block technology offered continuous train control with minimal wayside equipment and could handle the close headway of 60 sec required in the tunnel. The initial investment was considered to be reasonable and maintenance costs could be reduced. As a result, SEPTA proposed to prepare performance specifications for a moving-block system including communications-based technology.

Improving Boston Light-Rail Control System

The goal of MBTA is to regulate traffic as it enters the downtown tunnel. The technology should provide the proper train separation and keep headways above 1 min. It should also place the trains in proper sequence so that the correct berthing at Park Street can take place. The most important requirement is that the technology be able to make automatic adjustments to correct deviations in schedules. For longer delays, the system must be

TABLE 5 Estimated Costs of MBTA's Central Tunnel Communications-Based Train Control System (6)

Phase Description	Cost ($ million)
Computer Analysis	0.5
Design	4.0
Construction Phase Services	4.0
Replace Signal System	25.0
Install ATS	15.0
Incorporate Traffic Management System	5.0
Overlaid Communications-Based System	45.0
Total Cost	**98.5**

able to use the track and signal system to short-route and deadhead cars.

The system to be adopted by MBTA requires four system components: a new interlocking device and signal equipment, an ATS system, a traffic management system (TMS), and an overlaid communications-based train control system. These systems need to be integrated into one system including the associated vehicle-borne equipment. According to the information provided by MBTA during the International Conference on Communications-Based Train Control on May 9–10, 1995, in Washington, D.C., the project is estimated to cost $98.5 million, which does not include force account moneys. A breakdown of the cost is given in Table 5.

Dallas Area Rapid Transit Light-Rail Starter System

In 1992, construction began for the Dallas Area Rapid Transit (DART) LRT starter system, which consists of 32 km (20 mi) of double track and 20 stations at a cost of $841 million. DART's LRT system is scheduled to open its first segment of 16 km (10 mi) and 10 stations in June 1996, the second segment of 11.3 km (7 mi) and 7 stations in late 1996, and the third, 4.8-km (3-mi) segment in June 1997. The system will run in diverse operating environments including a 5.6-km (3.5-mi) segment in deep twin tunnels, a 2.4-km (1.5-mi) bridge spanning the Trinity River, a semi-grade-separated private right-of-way, within a street median, and through a vehicle-restricted transit mall in the central business district (CBD).

The control and communications equipment for DART's LRT system will be housed in a control center. The control system will provide full monitoring and remote control capabilities such as train stopping, vehicle movements on the mainline, revenue service delivery and control, delay management, ROW access, and emergency response coordination.

The signal system is designed to accommodate a 90-sec headway at a maximum operating speed of 105 km/hr (65 mph) with restrictions of 72 km/hr (45 mph) in unprotected line-of-sight territory and 32 km/hr (20 mph) through the CBD. There are 54 grade crossings, 34 of which are fully protected with warning gates. Activation of the gates is accomplished through one of all of the following: standard approach circuitry, train-to-wayside communications, and absolute block—traffic signal interface. Movement of LRVs in the CBD will be controlled by green light signals synchronized with the central traffic management signal system.

The components of the train control system include

- A communications transmission system to provide a link between the control center and locations within communicating territories via a fiber-optic cable; communication between the control center and locations within noncommunicating territories is via copper cable or dial-up telephone lines;
- A supervisory control system to transmit and receive status change indications and control signal devices and ventilation equipment;
- A central computer network consisting of a system overview display and control consoles for main-line operations, yard operations, and system management;
- A train stop control system to provide penalty stop protection for the trains in signalized segments;
- A train-wayside communication system to provide remote control capability for switch operation and commands to the signal system;
- Wayside absolute block signals to protect train movement within signalized areas; in nonsignalized territory, line-of-sight operating rules will apply; and
- Fully automatic couplers at both ends of the vehicle for all mechanical, pneumatic, and electrical connections between cars in a train, remotely controlled from the operator cab.

CONCLUSIONS

A major advantage of LRT systems is their capability to operate in diverse environments. The manual operation mode of LRT, however, has resulted in a larger number of train-vehicle and train-train collisions when compared with other fixed-guideway transit modes. Future LRT control technologies must therefore provide capabilities to monitor and control the entire fleet that operates on different rights-of-way and alignments. The train control systems should be capable of providing real-time, constant communication between the vehicle-track, vehicle-control center, track-control center, passenger-control center, and vehicle-operator and vehicle-control center for safe operation and maximum utilization of the track.

Current LRT systems equipped with ATP and with ATO and ATS are operating with shorter headways, increased capacity, and enhanced safety. An example is the Los Angeles Green Line, which runs on an exclusive right-of-way equipped with an ATC system and has drivers on board the vehicles who keep constant communication with the central control to provide for safer train operation.

Advanced technologies such as ATCS promise to allow economical, efficient, and safe train operation by incorporating a collision avoidance system that is capable of detecting and preventing impending collisions between vehicles for safer train movements, a feature that may solve the major LRT safety problem. Currently, the only LRT system operating with ATCS is the fully automated, driverless SkyTrain in Vancouver, Canada.

Additional effort in the development of advanced LRT control technologies for at-grade LRT operation with mixed traffic is needed. It is imperative to develop an improved on-board and wayside system to provide automatic location tracking and automated transmission of movement authorization coordinated with track sensors and traffic signals. Because most existing LRT systems will need to upgrade or replace their control and communication systems in the future and given the fact that funding is limited, it is also important that the new technologies be flexible enough to be compatible with the existing equipment, to allow phased improvements. To develop technologies and equipment that will significantly enhance LRT safety and performance requires transit equipment suppliers and LRT operators to work together to identify the needs, constraints, market potentials, and opportunities in technologies and financing.

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