Five Years of Successful Light Rail Operation

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The 5-year (1986–1991) operating experience of the Tri-County Metropolitan Transportation District of Oregon (Tri-Met) with Portland's Metropolitan Area Express (MAX) light rail service can provide transit agencies with models for high-capacity service over varying applications on the 15.1-mi MAX environment on railroad right-of-way (2 mi), through residential and commercial streets (5 mi), alongside two major interstate freeways (6 mi), and on downtown streets (2 mi). MAX performance in the areas of safety, access, ridership, average speed, mechanical reliability, maintenance requirements, and so forth indicate how different line sections and applications matured chronologically with the rail system.

The Metropolitan Area Express (MAX) light rail service operated by the Tri-County Metropolitan Transportation District of Oregon (Tri-Met) is Portland's first publicly owned rail transit and the region's first rail transit service since private companies dismantled the last of a once-extensive network in 1958 (*1*).

Focusing on varying characteristics of MAX's 15.1-mi operating environment and comparing the 5-year operation (September 1986 to June 1991) of four distinct design applications (designated by line section numbers) might assist other transit agencies with planning, construction, or operation of light rail.

Material herein, except as referenced, is the product of interviews with Tri-Met employees, who have daily responsibility for making something new to the Portland metropolitan region operate as if it had been operating for decades.

INFRASTRUCTURE

General Description and Geography

In Line Section I (LS-I), MAX operates as an Oregon Public Utility Commissioner-governed railroad on mostly single-track right-of-way, crossing streets and through a wooded cut at a top speed of 55 mph and protected along the two-direction, single-track segment by an automatic train stop (ATS) system. Vehicular and pedestrian traffic are regulated by standard railroad crossing signals and barriers from the eastern terminus, Cleveland Avenue station (milepost 15.1, elevation 345 ft), past the Ruby Junction Rail Operations Facility to Line Section II (LS-II).

In LS-II, MAX travels east-west at 35 mph in the median of a two-way street (East Burnside Street) along 5 mi of residential neighborhood past 500 properties with commercial centers concentrated at major intersections approximately 1 mi apart. MAX controls traffic signals to platforms located on the far side of these intersections, and vehicular traffic may only cross at these and a few other designated intersections. There is no median fence, and pedestrians cross between intersections at unsignaled, protected crosswalks along the 110-ft right-of-way. One-way automobile lanes border the track with left-turn/U-turn lanes at many intersections, and sidewalks and landscaping. Between Ruby Junction (milepost 12.8, elevation 258 ft) and 102nd Avenue (milepost 7.9, elevation 283 ft) are eight stations.

In Line Section III (LS-III), MAX parallels 6 mi of two interstate freeways (I-205 and I-84) on completely separated right-of-way accessible by stairs and elevators from pedestrian and automobile overpasses at three of four stations. The remaining station, a major transit center, is served by a dozen bus lines and is accessible to automobiles and pedestrians. MAX operations in this high-speed (55 mph) section are protected by an automatic block signal (ABS) system between 99th Avenue Station–Gateway Transit Center (milepost 7.0, elevation 291 ft) and 42nd Avenue–Hollywood Transit Center (milepost 3.9, elevation 158 ft) and east of Hollywood where LS-III continues for another 1.7 mi to Line Section IV (LS-IV).

In LS-IV, MAX traverses 32 blocks of downtown Portland on four streets at 15 to 25 mph, crossing the Willamette River on the Steel Bridge (owned by Union Pacific Railroad). Except on bridge lanes, MAX tracks are reserved for trains but mix with cross traffic, allowing vehicles and pedestrians to cross at almost every intersection. MAX stops at 15 stations between Lloyd Center–Northeast 11th Avenue (milepost 2.2, elevation 136 ft) and Galleria (milepost 0.1, elevation 78 ft). A maintenance facility, the Southwest 11th Avenue Terminus (milepost 0.0, elevation 89 ft), provides a turnaround in Portland's central business district (CBD) (*1*).

Track/Rail

Tri-Met's MAX rolls on two types of track rail: girder rail and T-rail. Standard T-rail is located in the yard and on the main line in LS-I, LS-II, and LS-III. In LS-IV, girder rail is imbedded in the street, flush with the surface and surrounded by a hard, rubberized substance to absorb train vibrations and prevent stray currents from deteriorating utilities (*2*).

The line is essentially double-tracked, except for the easternmost 2.2-mi section (LS-I). That section is single track with a second track provided at Gresham City Hall (midway) and at the outer terminal, Cleveland Avenue. In the heart of

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downtown Portland, westbound and eastbound tracks are a short block apart.

Three tracks are available at Southwest 11th Avenue loop (milepost 0.0) for vehicle staging and infrequent maintenance inspections. A third track at Coliseum Transit Center (milepost 1.6) is used to load passengers from special events and at Gateway Transit Center (milepost 7.0) for staging and for stubbing eastbound trains, increasing line capacity on LS-III and LS-IV between Gateway and downtown Portland. Frequent track crossovers compensate for main-line obstruction problems requiring temporary single-track operation. En route equipment failures have been rare, but at six spots along the line a car can be dropped to await maintenance assistance.

Power Supply

Portland General Electric (PGE) and Pacific Power (PP) supply alternating current (AC) to 14 substations located at or near passenger stations. PGE & PP deliver power to the substations at 12,500 volts of alternating current (VAC). Passing through AC circuit breakers into transformers, 12,500 VAC is reduced to 640 VAC, which is converted from AC in a solid state rectifier to a nominal 750 volts direct current (VDC) and transmitted through circuit breakers to the overhead wires.

Trolley wire, a more rigid overhead power system suspended from cross span wires and requiring precise alignment, is located on the west portion of LS-IV in downtown Portland, across the Steel Bridge to Coliseum Transit Center, and in the Ruby Junction Yard.

Catenary wire, a less rigid system of messenger wire hung from span to span in a naturally curving sag, supports contact wire hanging from the messenger wire by stringer wires and is located over all LS-I, LS-II, and LS-III main-line and auxiliary tracks. Stringer wires vary in length as messenger wires sag, holding contact wires level above the track. Catenary wires stagger laterally from pole to pole, maintaining uniform contact and wear on light rail vehicle (LRV) pantographs.

Isolators section the overhead power system, allowing one section to shut down without affecting the entire system. Power failures at individual substations (radio signaled to rail control and indicated visually by flashing lights) do not shut down the line.

Power is grounded through the track, which carries approximately 50 volts of DC (not a hazard to personnel or the general public) back to substations and signal paths for signal track circuits. Track is also sectioned, preventing electrical current flow from one rail to another and primarily used in ABS to separate signal track circuits. Yard track is sectioned from the main line and from the shop (*2*).

Signals

Train operators and train presence control the varying line signal configurations. MAX combines the use of two types of signals: railroad (vertical bar: proceed; horizontal bar: stop) and color (green: proceed; amber: caution; red: stop).

ABS and an ATS component protect trains from human or signal failure in LS-I and LS-III, tripping relays in any violating vehicles, stopping them, and preventing two trains from entering LS-I single track from opposite directions or two high-speed trains from being on the same block of LS-III track at an unsafe distance. Similar shutdown protection is built into each vehicle's speed governor, preventing speeds higher than 57 mph.

A preemption signal system governs train movement in LS-II and the eastern portion of LS-IV (Lloyd Center to Coliseum). As trains proceed over them, output from call loops embedded under tracks approximately 1,400 to 1,600 ft ahead of intersections preempt and phase traffic lights to give trains priority to proceed and directing automobile and pedestrian traffic to stop and wait.

Trains proceed on white vertical signals and stop on yellow horizontal signals that flash for approximately 5 sec before changing. Traffic signals in LS-IV are augmented by large, red signals that flash Train as trains approach or proceed through intersections.

Trains exceeding LS-II's 35 mph maximum speed beat the preempt to the signal. Trains slower than 20 mph miss the signal. After passing signals, trains pass over checkout loops returning signal priority to regular traffic.

In LS-IV trains do not have preempt power over traffic signals, but operators exercise control through a wayside signal control system (Vetag). At stations, operators stop trains over loops embedded in streets, illuminating Vetag buttons on LRV control consoles. Operators depress the call button, beginning a cycle that enters trains into normal traffic signal sequences rather than favoring trains over regular traffic (*2*).

Automatic Block Signal System

The ABS system, a series of consecutive blocks (sections of track with defined limits for train movement) equipped with train-actuated, wayside signals that govern train passage, is located in LS-I and LS-III. ABS governs electric switches, crossing gates, and traffic signals in its territory, guaranteeing that only one train occupies each block at a time.

Track circuits in each block detect trains. At the ends of each block, signals define the occupancy of the next block and, in some cases, the next two blocks. A device located between the rails trips an irreversible maximum service brake application in trains failing to stop at a red signal. ATS sounds an audible alert, lights up the ATS trip annunciator on the LRV control console, and registers on the ATS trip counter in the LRV operating cab (*2*).

Train detection activates main-line signals. Operators clear signals that govern train movement between main-line and auxiliary tracks by route selection at key-by boxes.

Switches

Normally electric switches govern main-line train movement. When trains occupy the track, track circuits request a normal route for main-line operation. If the requested block is not occupied by another train, ABS properly aligns and locks the switch point for the route, displaying appropriate signals.

Five slap (spring stay) switches located only in the yard throat at Ruby Junction allow trains in a trailing move through a switch to use wheel flanges to throw the switch and proceed on the normal route without manually throwing the switch. All other yard switches are manual (*2*).

Yard and Facility

Entering the yard from the main line, trains first pass through the yard throat that connects the yard to the main line tracks and either maintenance or storage track ladders: maintenance tracks on the west side of the yard; storage tracks to the east of Ruby Junction Rail Operations Facility.

Wash and blow-down tracks complement storage and maintenance tracks, and a run-around track enables vehicles to circle the facility and enter either end of the three-story building that houses administrative offices and rail control on the third floor, maintenance training and special shops on the second floor, a machine and vehicle shop on the main floor, and parts storage in the basement.

Its design is simple, accommodating no more than two vehicles on each track, preventing the "hemming in" of a vehicle, which invariably necessitates moving a vehicle still under maintenance. The overall building layout, conducive to productivity and enhancing working conditions, is open, bright, and airy. Hand washing facilities on the shop floor minimize employee time away from vehicles or other tasks. A foreman's office halfway down the floor allows full view of all work areas.

Stations

The 30 MAX stations differ slightly as dictated by function. All stations are just over 200 ft long to accommodate two-car trains. Gateway station is slightly longer.

LS-I and LS-III station platforms either surround or border tracks. LS-II station platforms are situated on the far side of intersections, offset, essential to the traffic signal preemption, because trains can be timed through intersections without allowing for station stops of varying length, and accommodating left-turn/U-turn traffic lanes. LS-IV station platforms are widened city sidewalks on one or both sides of the street.

Train customers use stairways from arterial and pedestrian overpasses to access three LS-III stations on the north side of I-84 at highway grade. Passengers unable to use stairs use an elevator.

Transit centers have more than one Autelca ticket vending machine (TVM). All stations have at least one TVM, except west- or southbound LS-IV stations west of the Willamette River. The TVMs are on platforms except at 82nd and 60th avenues where the TVMs are installed at the head of the stairs on overpasses. A July 31, 1991, ordinance makes these two platforms open only to passengers with proof of payment (valid passes, tickets, or transfers).

Most stations have passenger shelters with upright supports ringed with leaning rails designed for waiting passengers to lean on and benches of wrought iron and wood slats.

Accessibility for Handicapped Passengers

Wayside lifts located on each platform at the front of each train enable riders in wheelchairs and those who cannot climb stairs to board trains. Each MAX train carries two customers in wheelchairs. FY 87 daily lift use ranged from 10 to 20; FY 91, near 50.

Transit Centers

Five transit centers (TCs), Gresham (LS-I), Rockwood (LS-II), Gateway and Hollywood (LS-III), and Coliseum (LS-IV), afford passengers off-street transfers from bus to bus or bus to train or train to bus (Figures 1 and 2). Transfers are timed at Gresham TC and Gateway TC.

Gateway TC, a unique design, allows 12 bus lines to encircle three tracks. Passengers wait on two westbound platforms and one eastbound platform. The main-line westbound track is served by two platforms enabling all 16 doors on a two-car train to be opened and the typical 50 or more passengers waiting for each morning train to board quickly.

East of westbound trains (headed north at Gateway) are stalls for six Tri-Met feeder bus lines serving areas east of Gateway and for one bus line serving Vancouver, Washington, to the north. Buses and trains are scheduled for timed transfers primarily outside peak hours, but some peak buses arrive at the same time as trains, allowing westbound passengers to transfer from feeder buses to trains in a few steps. West of eastbound trains (headed south at Gateway) are stalls for five city bus lines. The center track is used to reverse trains between Gateway and downtown.

Bus passengers wait in small shelters located near each bus bay; MAX passengers use open metal and glass shelters reinforced with windscreens.

Park and Ride Lots

Five lots provide Tri-Met passengers free parking in just under 1,800 spaces at Cleveland Avenue (377 spaces) and Gresham City Hall (285 spaces) (LS-I); at 181st Avenue (252 spaces) and 122nd Avenue (405 spaces) (LS-II); and Gateway Transit Center (480 spaces) (LS-III) (*1*).

Vehicles

Tri-Met's LRVs, manufactured and assembled in 1981 by the French-Canadian Bombardier Corporation in Barre, Vermont, cost $800,000 per vehicle. The current replacement cost is approximately $2 million each. The car body is made of low alloy steel, fluorescent lights illuminate the interior, and a roof-mounted, forced-air system ventilates the 87,090-lb (approximately 44-ton) LRV. It seats 76 and comfortably stands an additional 90 for a total of 166 passengers. Under crush conditions, each LRV can carry 256 customers; each two-car train, more than 500.

Through train pantograph contact with overhead wires, 750 VDC is delivered to the static converter and transformed to 37.5 VDC for doors, wipers, exterior lights, radios, and other low-voltage systems. The converter supplies 37.5 VDC to the inverter turning 37.5 VDC into 120 VAC for interior lights, destination signs, heating systems, fans, and blowers. In a power failure, each LRV has an on-board battery system to provide backup 37.5 VDC for approximately 1 hr.

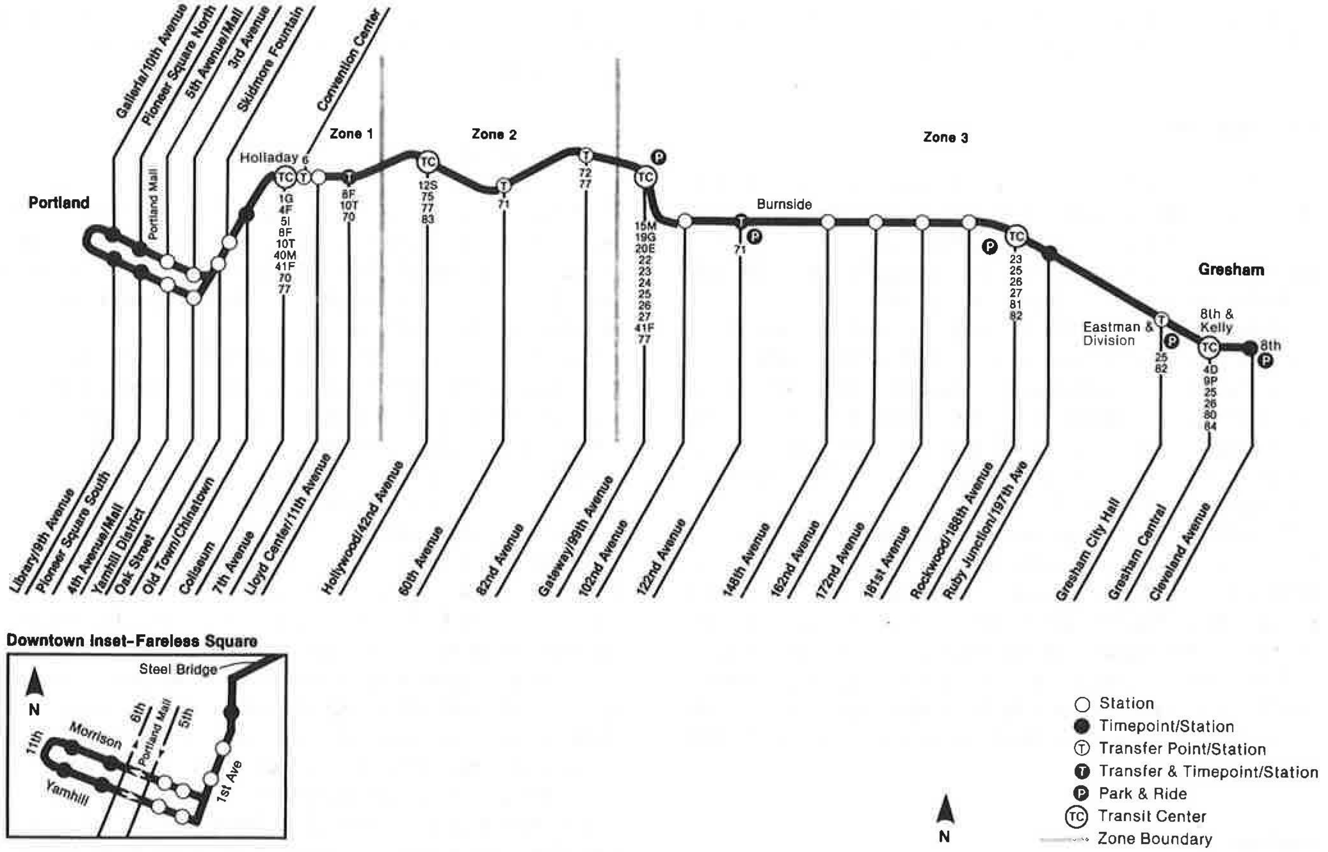

FIGURE 1 Tri-Met's MAX light rail service connecting downtown Portland with suburban Gresham.

A computerized electronic control unit on each LRV governs on-board train systems to blend braking and acceleration, to train-line systems in two-car consists, and to control safety features. The maximum 55 mph operating speed is governed by an overspeed restrict that brings the train to a maximum service brake stop if 58 mph is reached.

Operators control acceleration and braking by moving a motoring drum handle through 16 positions: six acceleration, six braking, three speed maintains, and one coast position. Traction motors located on the two extreme trucks of each LRV draw 550 to 600 amps in propulsion modes, providing 192 to 250 horsepower and accelerating at a rate of 3 mi/hr/sec.

Braking, provided by a blended dynamic/spring-applied disc hydraulic system that includes three brake types (dynamic, friction, and track), uses dynamic brakes as the primary system, reversing traction motors and dissipating heat generated through resistors on the car roof until car speed is reduced to 3 mph.

Disc brakes that bring trains to a complete stop (operating at 3 mph or less) are friction brakes, applying brake pads to train wheels on all three trucks. Disc brakes on end trucks are used in normal braking. The larger pads of the disc brakes on the center trucks are used only in emergency situations.

Track brakes, spring-suspended electromagnetic units on each truck, become attracted to and contact the rails for maximum braking power. Operators can apply track brakes manually for low-speed, precision stops. Track brakes also deploy automatically in emergency situations. Disc and track brakes with sanders are applied with maximum force.

Maximum service brake (blended braking of all braking systems) decelerates at 3 mi/hr/sec. In an emergency, however, the maximum braking (MB) rate is 4.7 mi/hr/sec—disc and track brakes not blended—in which traction motors draw 415 amps. Even with MB, trains need 750 to 800 ft to stop completely from a speed of 55 mph (*2*).

Communications

A console radio in each LRV cab, the primary means of communicating with the controller, is supplemented by a portable radio for use should operators leave the cab or primary console radios fail. Transportation and maintenance each have two reserved channels for their primary use. Before using the radio, employees verify that the channel is clear and direct all transmissions to controllers unless controllers authorize direct communications with other employees (*2*).

Rail Control

Located on the third floor of the rail operations facility, rail control serves as the main-line command center and sign-in

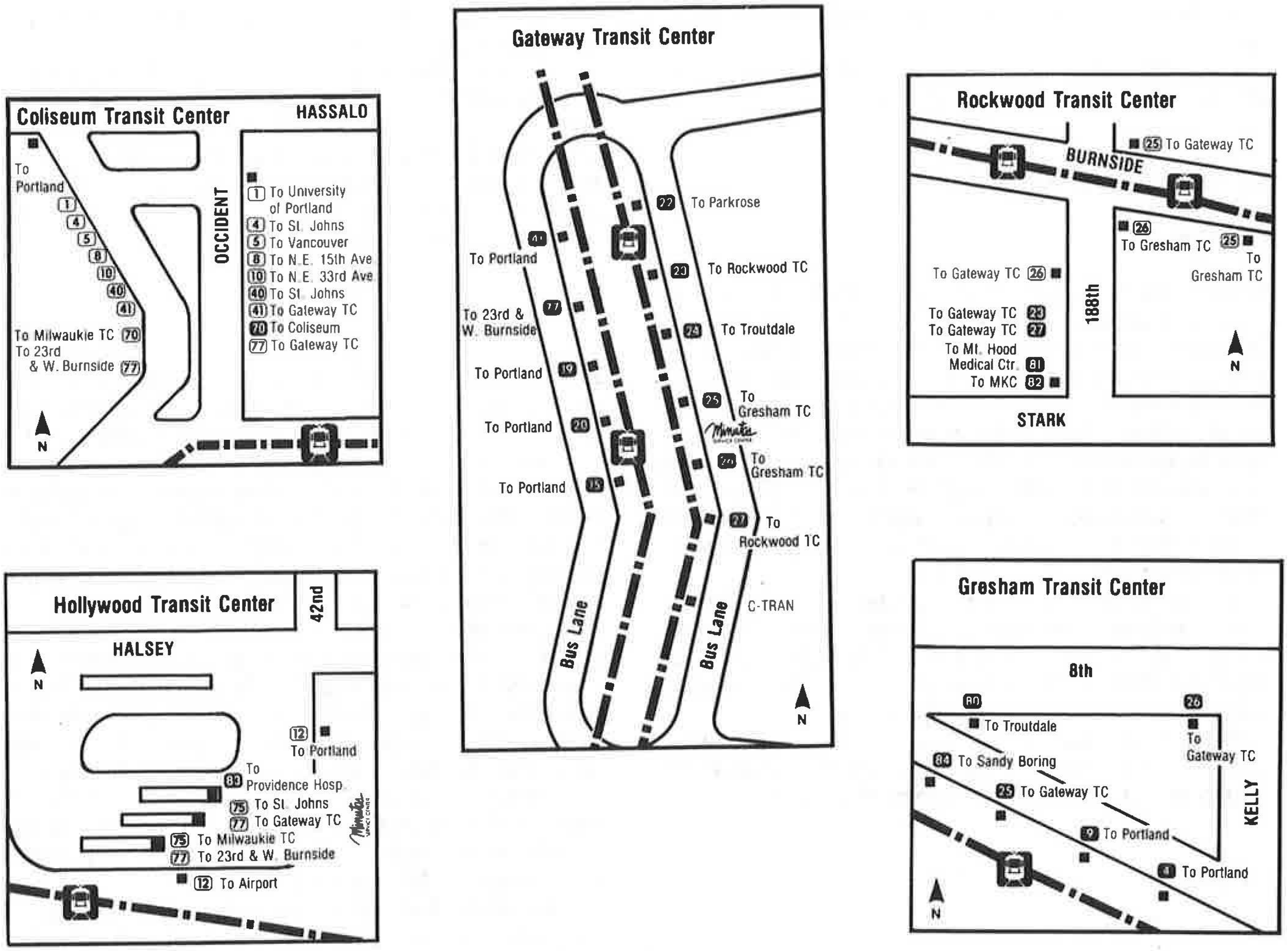

FIGURE 2 Transit centers.

station for operators where they report to work, pick up pouches, and review special orders.

Designed to low-tech specifications, rail control includes an open channel two-way radio with several channels, a magnetic yard/alignment board, and computer equipment to monitor ticket vending machine and substation security alarms. (Substation alarms were originally only flashing lights on site.) Controllers use a word processor to log major events and provide 24-hr coverage, combining duties of bus station agents and dispatchers. Controllers are responsible for ensuring safe operation of the entire light rail system, including the following:

- Covering all runs;
- Assigning trains and extra-board work;
- Issuing train orders, special instructions, pouches, portable radios, flashlights;
- Ensuring that equipment works properly;
- Assisting operators to troubleshoot train defects; and
- Coordinating light rail activities with police, fire, emergency, and county and municipal services.

Assisting the controller, rail supervisors work along the right-of-way to do the following:

- Conduct on-time performance checks;
- Assist in troubleshooting defects;
- Maintain system safety;
- Serve as primary investigators of rail accidents (taking pictures, inspecting damage, interviewing witnesses, conducting drug testing, and completing all necessary reports);
- Perform evaluations of and make suggestions to improve operator performance;
- Assist in customer relations (investigating complaints, providing timetable; and ticket vending information);
- Assist in cutting or adding cars to trains; and
- Operate trains in revenue service if necessary.

Following directions and working under supervision of the rail controller or supervisors, operators do the following:

- Follow all rules, procedures, and other special instructions;

- Take charge and operate trains on established schedules; and
- Use best judgment to provide safe and reliable service to the public and protection of property (*2*).

OPERATING EXPERIENCE

Financial

With a 1990–91 budget of $7,812,380, about 142 percent of the first year's projected budget ($5,511,796), MAX has experienced 5 years of steadily increasing expenses brought about by increasing service levels, phased-in maintenance staff, and beginning major maintenance on used equipment no longer under warranty. Transportation and maintenance employees have increased from 78 to 124; of the increase, transportation accounted for 12 additional employees; rail maintenance, 34. Maintenance staffing was phased over a 5-year plan because of manufacturers warranties and the relatively low maintenance in the first years for new LRVs.

Transportation's FY 87 operating budget of $1,792,531 covered 1 director, 1 manager, 8 controller/supervisors, 1 secretary, and 26 operators; its FY 91 budget of $2,309,302 supported 1 director, 1 training supervisor, 10 controller/supervisors, 1 secretary, and 36 operators.

Maintenance began revenue operation in FY 87 with a budget of $3,719,265 to support 51 employees, compared to a FY 91 budget of $5,103,018 to support 85 employees (*3*).

Maintenance

Vehicles

Routinely, car interiors are cleaned nightly; exteriors, every other day. Two of the 26 cars have been evaluated for overhaul needs, and a program is under way to incorporate some overhaul steps into the preventive maintenance program.

Tri-Met's maintenance team has, in 5 years of operation, found very few major difficulties with MAX LRVs. Any vehicle has problems that usually occur on most used parts. The major problems encountered on Tri-Met's 26 LRVs involved motors, doors, and brakes.

During FY 87 motors developed flashover problems because of improper interpole location. The contractor made necessary modifications on all motors; service was affected before modifications were complete only by lesser acceleration rates—noticed at first by customers, but something to which they acclimated quickly.

The weight and size of the swing plug-type doors on the LRV considerably flexed the framework supporting cam switches controlling door operations. A modification relocated these cam switches to an area ensuring rigidity and proper, consistent door operation. Operators' ability to activate the doors, enabling passengers to open them only when needed (not every door has to open at every station), keeps door problems to a minimum.

Extreme wearing of the friction brake actuator cylinder brought on by the force required to stop the vehicle caused brake fluid leaks. Modification of the actuator curbed wearing and, subsequently, leaks.

Rail maintenance personnel discovered that more frequent wheel truing (shaving minute amounts of material from the outer circumference of the metal tires) resulted in less material being shaved and tires lasting longer. Over time, a program was developed to schedule each car for wheel truing every 20,000 to 25,000 mi, the frequency being determined by reviewing the worn wheel profile.

Right-of-Way

Routine maintenance of way includes walking inspection of all 15.1 mi each week and monthly adjustment and lubrication of switches. A crucial design problem causing additional labor costs for LS-III between Gateway and Lloyd Center is the inaccessibility of the track except from stations or by highway/rail (hi/rail) vehicle. In emergencies parking along the freeway may become necessary. Additional labor costs result from the extra time crews take to arrive at the point of maintenance. A service road in the right-of-way would be a solution.

Tri-Met already has had to replace a right-of-way infrastructure component: grade crossings not designed to cope with traffic volume and weight. A decision to detour a truck route may have played a part in the breakdown of hard rubber modules and their replacement within 6 years of installation, along with shortcuts, low bids, and little aggressive cooperation with traffic and design engineers to determine eventual road use. Failed material is being replaced with precast, prestressed concrete panels expected to last for at least 10 years and to withstand bus and truck traffic.

Other extraordinary costs include vandalism cleanup and replacement especially at stations designed with large glass windows which were targets for ballast rocks made handy by trackway design. Material costs ranged between $20,000 and $25,000 annually added to cleanup labor costs.

Designing stations with as little glass as possible and paving LS-I, LS-II, and LS-III right-of-way for several hundred feet on either side of stations may have reduced vandalism costs substantially. Staffing the design team with experienced operations personnel to work with architects would help incorporate operating possibilities in the final design.

Frequent urination in elevators providing access between overpasses and LS-III stations along I-84 deteriorated support materials under tile floors, forcing renovation that included replacing underflooring material and installing shallow stainless steel "bath tub" floors. Renovation did not stop the urinating but did prevent structural materials from deteriorating.

Ticket vending machines (TVMs) have been extremely reliable and easy to maintain. Locating TVMs to protect machines and customers from the elements would improve future operation and maintenance. One major TVM improvement was installation of a radio alarm system, signaling any intrusion or attempted intrusion directly to rail control. Original audible alarms were only on site.

Wayside lifts, simple elevators with a drawbridge facing the vehicle, have also been easy to maintain but are subject to the elevator urination problem. A design flaw that allowed rainwater to fall on passengers and operators was corrected by adding to the rain gutter.

Graffiti on vehicles and right-of-way is a moderate problem, happening in spurts and handled as it occurs. To keep the problem under control, never place an LRV in service with graffiti or damaged upholstery; immediately remove all graffiti and repair damage on the right-of-way.

Stations are pressure-washed at least four times annually, and most heavily used stations are pressure-washed upwards of eight times annually, a very labor-intensive, expensive process. All stations are cleaned daily; some, twice daily. Special problems are handled as they arise.

Heavy maintenance of way is usually conducted when MAX is not running (between 1 and 5 a.m.). Routine maintenance of way sometimes spurs attendant labor problems e.g., catenary line counterweight settings must be performed at mean temperatures—not always achievable during early morning hours when crew are assigned.

Time and material costs to service any large portion of LS-IV track (where girder is embedded in an insulating substance to contain stray currents and dampen vibration and noise) are unknown. Grinding or welding any LS-IV track would require chipping away the surrounding substance and replacing it under temperature-accurate conditions.

Using a privately owned river span (the Steel Bridge in LS-IV) has posed both operational and maintenance problems, making operations unreliable. The bridge frequently has been inoperative, and Tri-Met's bus division has deployed buses to transport passengers via another bridge (standard operating procedure for accidents or equipment problems that interrupt service on both tracks of any section).

Maintenance time windows needed to perform specific tasks have been restricted when MAX handles special events such as the Rose Festival, marathons, and other races.

Service and Schedules

In peak hours 22 vehicles in 10 two-car and 2 single-vehicle morning trains and 11 two-car afternoon trains carry heavy loads. In midday, evening, and weekend operation, eight two-car trains are the rule; eight single-car trains, the exception. The FY 91 service configuration, however, was not always so.

Running times and quantity of service required to transport passengers effectively, essential factors in producing transit schedules, made it obvious to Tri-Met's rail operations team before start-up that initial running time estimates were low. Initial scheduled times, however, have held up with relatively minor adjustments.

Since FY 87, several factors have affected running times. Adverse effects are as follows:

- Fifty daily wheelchair uses for 84 train trips in each direction daily place chances of a wheelchair being loaded on each round trip at 60 percent. Providing accessible service has made Tri-Met an asset to the handicapped community, but necessary schedule recovery time is included in terminal layovers.
- Four additional round-trip LS-IV stops have been added, two at the Pioneer Place office and retail development to the west side of the river and two at the Oregon Convention Center to the east.

Beneficial effects are as follows:

- Installation of the train-to-wayside (Vetag) signal preemption system allows smoother and more efficient schedules downtown.
- Right-of-way on all but 500 ft of track over the Steel Bridge (LS-IV) is exclusive or reserved.
- Signal preemption is used throughout LS-II and LS-IV.
- Sufficiently wide station spacing in LS-I, LS-II, and LS-III permits reasonably fast operation.
- Self-service fare collection permits all doors to be used freely at each station and minimizes dwell time.

Balancing these factors permitted MAX to hold its own on running time. Increased vehicular traffic, ridership, and additional stops has not had any seriously detrimental effect on MAX operation.

Since FY 87 Tri-Met has made incremental changes to MAX service. Public interest in a highly publicized start-up resulted in heavy loads, especially during weekends and off-peak weekday hours. "Curiosity" patronage eventually leveled off as peak business ridership increased in the first 2 years (FY 87 and FY 88) of operation. Beginning in mid-1989 MAX total ridership began to increase with subsequent fiscal years showing patronage gains of about 13 percent (*4*).

Planned peak weekday schedules of 20 of the 26 LRVs with 12-min headways and day base headways of 20 min proved too little, as popularity forced immediate improvement of day base headways to 15 min. Peak headways have been further adjusted and improved to accommodate growing ridership, particularly in the heart of the morning peak.

FY 91 schedules employed 22 cars with trains operating at 6.2 min in the "peak of the peak" half-hour period. Creative scheduling techniques to derive maximum effective use of the available equipment and reduce overcrowding have included weekday splitting of a two-car outbound train at Gateway into two one-car trains to increase capacity between the two most heavily loaded inbound trains from 7:25 a.m. to 7:35 a.m.

Frequent schedule adjustment keeps pace with load increases and has balanced loads and minimized loss of customers from peak period overcrowding. Tri-Met service standards for MAX call for the number of riders not to exceed 76 passengers per car (a full, seated load) east of 122nd Avenue in LS-II in either direction (*5*). Counts during summer 1991 indicated that 8 of the first 13 weekday westbound trains exceeded that standard as far east as 197th Avenue.

Special Events

To emphasize the regional nature of MAX service, the Friday, September 5, 1986, service start-up followed three public ceremonies (9 a.m. at Gresham City Hall, 10:30 a.m. at Gateway and noon at Pioneer Courthouse Square). More than 1,000 attended the Gresham ceremony, more at Gateway, and about 11,000 downtown.

Beginning at about 1 p.m. and continuing all weekend (5 a.m.–1 a.m.), Tri-Met operated 12 trains at 10-min headways carrying more than 200,000 celebrants free on the innovative transit mode. Businesses and private citizens contributed more than $200,000 to fund entertainment and refreshments at five stops along the way. Tri-Met returned 200,000 tickets to those contributors, priming the ridership pump for the next several months.

With no major accidents, no major injuries, and few lost children, MAX demonstrated to operators and controller/supervisors how light rail can meet special needs with special service.

In regular service, the need of Portland's Memorial Coliseum was obvious. A third (special events) track at the Coliseum Transit Center allowed rail supervisors to hold back one or more cars, normally cut from a two-car train after the evening commute, for crowds leaving the Coliseum from Trailblazers basketball games, concerts, and other events (circus, conventions, etc.). Extra service accommodated the first wave; trailing riders take regular service.

Christmas holidays and spring break have been marketing opportunities to showcase MAX for new customers. The surge in holiday ridership calls for two-car trains most of the day and night and sometimes volunteers on platforms to help newcomers.

The 1987 Rose Festival was MAX's first "crush" test since opening weekend crowds. Since 1987 MAX has not let a Rose Festival crowd down, carrying more than 10 percent (*4*) of the close to 500,000 parade watchers downtown and shuttling them afterwards between waterfront Festival Center (First Avenue Station), the Lloyd Center, Hollywood, Gateway, Rockwood, and Gresham. In 1987 a Gresham business owner reported having seen a sailor near his shop for the first time ever during the Rose Festival. The festival draws more than 5,000 sailors and marines to the Rose City seawall each year; MAX lets them see more.

Bus Connections

Tri-Met's service standards call for bus routes to maximize connections with rail stations when riders would benefit (*5*), a goal accomplished in 1986 by restructuring service that crosses and parallels MAX.

For LS-I, LS-II, and Gateway, bus routes were changed to provide convenient MAX access from as far south as Southeast Division Street (2 mi south of and parallel to East Burnside). Timed bus connections were given priority to facilitate local travel with bus-to-bus connections as well as train-to-bus connections.

Feeder lines replaced all radial lines extending from the east side into Portland's CBD east of Gateway and north of Division Street, and converged on Gateway Transit Center for timed connections with MAX trains, between feeder lines, and five Portland city bus lines (on streets parallel to MAX), with one line serving Vancouver, Washington (operated by C-Tran), and with each other. Some feeder lines converged on Gresham Transit Center for timed connections with each other and MAX, and some also met MAX at Rockwood but without timed connections.

Tri-Met opted for this service over a grid of north-south crosstown lines to preserve east-west movement patterns Tri-Met traditionally provided to the area and provide access to MAX. A full set of crosstown routes was not within the agency's financial means in FY 87, so limited resources were allocated only to crosstown service on 122nd Avenue and 181st/182nd avenues where housing density and commercial development suggested maximum ridership potential.

Timed transfer meets at Gateway were scheduled for 24 and 54 min after each hour, a pattern retained during peak hours when additional meets were inserted as needed at 9 and 39 min past the hour.

Major route restructuring was not needed in the rest of LS-III and LS-IV, because Tri-Met restructured city and eastside service in September 1982, putting in place a basic pattern of crosstown lines needed to support light rail service. Two major objectives of LS-III and LS-IV changes called for nondowntown bus-rail connections for nondowntown trips whenever possible and for MAX to replace a heavily used bus line (on Northeast Sandy Boulevard) as the urban trunk line for northeast Portland. The resulting radial line on Sandy Boulevard was re-routed to Portland International Airport, initiating the first direct bus service between Portland's CBD and the airport.

A single 15-min crosstown line replaced three radial and one crosstown overlapping lines on portions of two east-west streets, connecting MAX at Gateway, Hollywood, and Coliseum Transit Centers, continuing west over the Steel Bridge to Northwest Lovejoy Street and breaking up a long circular line that ran from northeast Portland to Lake Oswego via Beaverton.

To simplify and coordinate passengers' orientation to MAX service from the downtown reference point, the Blue Snowflake stops (one of seven designations used to identify geographical sections of Tri-Met's service area) were removed from the Portland Mall on Southwest Sixth Avenue. MAX was designated the only Blue Snowflake service from downtown Portland; its feeder buses serve the rest of that geographical area (*6*).

The FY 87 bus service has continued for the last 5 years with minor adjustments as patronage and requests for service warranted. Average weekday bus ridership in the Blue Snowflake service area (LS-I and LS-II) has grown 6.4 percent from 3,550 in FY 87 to 3,777 in FY 90. Ridership for crosstown city bus lines feeding MAX (LS-III and LS-IV) has increased 14.2 percent from 23,485 in FY 87 to 26,828 in FY 90. FY 91 line performance figures are not available (*4*).

Ridership

MAX weekday ridership has grown 20.0 percent from a FY 87 average of 19,500 boardings to an FY 91 average of 23,200 (Table 1). During FY 87, because of budget considerations, Saturday, Sunday, and, consequently, weekly and monthly ridership were not measured consistently enough to produce reliable figures, so FY 88 statistics are used as the benchmark for those numbers.

Since FY 88 MAX Saturday boardings have dropped 4.5 percent from 19,800 to 18,900 in FY 91. Sunday ridership increased 5 percent from a FY 88 figure of 10,000 to 10,500 in FY 91. Weekly ridership increased 13.3 percent from 128,000 FY 88 boardings to 145,000 in FY 91. Monthly total boardings averaged 550,000 in FY 88 compared to 620,000 in FY 91, a 12.7 percent increase, and boarding rides per service hour

TABLE 1 MAX Weekday Boardings and Percentage of Total Boardings by Line Section (*4*)

Line Sections	FY87	% Total	FY89	% Total	FY91	% Total
I. Railroad	2,600	12.5	1,808	9.9	2,376	10.5
II. Residential	3,848	18.5	3,266	17.9	4,352	19.2
III. Freeway	3,972	19.1	3,845	21.1	4,246	18.7
IV. Downtown	10,378	49.9	9,375	51.4	11,749	51.7
TOTALS	20,800	100.0	18,244	100.3	22,713	100.1

increased by 14.0 percent from 151.34 in FY 88 to 172.57 in FY 91 (*4*).

Station Use

A Tri-Met on-board ridership survey published in June 1987 identified Pioneer Square stations as the most used stops (with 14 percent of all boardings), with Library, Lloyd Center, and Gateway a close second (with 8 percent each). Weekends, however, saw most boarding activity shift to Lloyd Center (12 percent) and Library (10 percent); Pioneer Square (9 percent), Gateway (7 percent), and Skidmore Fountain (7 percent) followed close behind.

In FY 89 Pioneer Square stations continued to be the most used (14.8 percent) followed by Gateway (9.3 percent), Library/Galleria (7.9 percent), and Lloyd Center (7.8 percent). In FY 90 the Fifth and Fourth Avenue stations opened just two blocks east of the Pioneer Square stations, and the Convention Center station came on line early in FY 91. Although the addition of these four round-trip stops caused a shift in station use, LS-IV increased its share of ridership to over 50 percent (*7*).

PROGRAMS

Safety

An extensive FY 86 outreach effort aimed at schools and community groups along the MAX line resulted in hundreds of individuals viewing videotape productions pointing out potential safety problems. The objective was to make the community aware that it had a new "neighbor" that is larger and quieter than any motor vehicle—a new aspect of everyday life with which they would have to cope in a safe manner.

Despite efforts to educate motorists about the "new kid on the block," accidents, primarily at intersections, typically involved drivers who ignored signalized or signed intersections (Table 2). Accidents have been dramatically reduced in the last 2 fiscal years. It was at that time that signage (the flashing Train lights) and computerized signals (Vetag) were introduced.

The vast majority of MAX accidents have occurred in LS-IV, in the CBD. No accidents have ever occurred at LS-I gated crossings over the entire 5-year operation.

Three fatalities have been recorded. Two occurred at night in LS-III along I-84. Pedestrians got on the right-of-way, in one case on foot from the Lloyd Center station, walking east on the eastbound track, and in the other case after parking a car on I-84 and climbing concrete barriers to walk west on the westbound track. The third fatality occurred at an intersection in LS-IV during daylight hours after a motorist turned in front of an LRV, which partially crushed the vehicle.

The LS-III incidents are being studied with an eye to possibly installing intrusion alarms and improved lighting along high-speed sections of track.

Revenue Collection

MAX revenue collection includes two distinct programs: first, the daily collection of revenue from 68 ticket vending machines (maintained by rail maintenance) and currency processing at agency facilities; and second, the checking for proof of payment by fare inspectors. Both functions are administered by the revenue section of Tri-Met's finance and administration division.

Tri-Met contracts daily revenue collection and transporting services to a private, armed guard security firm and to an armored truck firm. Revenue is collected each morning; bank deposits are made each evening. Revenue section supervisors coordinate daily schedules for both services and perform checks and balances for these activities.

Eight full-time fare inspectors carry out inspection activities, working 10-hr shifts 7 days a week during all MAX operating hours under the direction of a chief fare inspector and a dispatcher. Five inspectors work three different shifts: 6 a.m. to 3 p.m. (two inspectors); 11 a.m. to 9 p.m. (one inspector); and 3 p.m. to 1 a.m. (two inspectors). Nine extra fare inspectors supplement the full-time staff. The extras are full-time bus operators.

Two changes made over the past 5 years have contributed to enhancing both employee job satisfaction and inspection productivity. One was the change to a 10-hr/day, 4-day work week from the previous 8-hr/day, 5-day week. This change resulted in a rotation of 3 days off for fare inspectors, enabling

TABLE 2 Accidents Involving MAX by Fiscal Year

TYPE	FY87	FY88	FY89	FY90	FY91	Totals	% of all
Intersection	29	26	31	11	11	107	42.8
Turns in front of LRV	13	10	25	6	**	**	**
Right Angle Collision	16	16	6	5	**	**	**
Head-on	0	0	0	0	1	1	0.4
Sideswipe	1	1	0	0	1	3	1.2
Rear-ends	0	0	1	0	0	1	0.8
LRV/other	0	0	0	0	0	0	0.0
Other/LRV	0	0	1	0	0	1	0.8
Pedestrian	5	4	1	2	4	16	6.4
In crosswalk	0	1	0	1	**	**	**
On platform	2	1	0	1	**	**	**
In Right-of-way	3	2	1	0	**	**	**
LRV hits object in r-o-w	33	5	11	17	19	85	34.0
Derailments	0	0	0	0	0	0	0.0
Others	2	3	13	15	4	37	14.8
Total by FY	70	38	57	45	40	250	100.0
% of all accidents/all FYs	28.0	15.2	22.8	18.0	19.2	100.0	

** figures not available

them to focus more attention on performing inspection-related assignments with the additional 2 hours of work daily.

The second change was the relocation of the fare inspectors' office to Coliseum Transit Center (LS-IV) on the MAX line, eliminating approximately 1-1/2 hr daily travel time for each inspector between the former report area at Tri-Met's administration building and the MAX line, approximately 3 mi away.

A fare inspection plan is being developed that will assess fare inspection needs over the next 5 years, looking at staffing needs and deployment options for both buses and MAX leading up to the 1997 estimated start-up time for westside MAX. A staff of 25 full-time fare inspectors is envisioned (more than double the current number) with a gradual staff increase each year to reach full strength by 1997, eliminating a sudden increase in inexperienced fare inspectors and providing an opportunity for expanded bus inspection and staff training in the interim.

A 1990 fare evasion review of the Tri-Met system estimated that MAX riders contributed $3 million annually in fares. Monthly levels of inspection varied from approximately 50,000 to 70,000 passengers, and the fare evasion rate varied from approximately 4.3 to 6.9 percent. The average evasion rate was 4.81 percent, which translates into an estimated revenue loss of $122,580. Total fare evasion for both MAX and buses was estimated at $350,000 annually. Fare inspection operating costs are $410,000 annually.

Fare inspectors also provide invaluable customer information services on board MAX and at platforms, telling customers (including tourists and visitors) how to use bus and rail service, how to purchase fares, and so forth. Fare inspectors also act as a crime deterrent and are credited with lowering vandalism and graffiti incidents, giving the public a sense of security because inspectors can summon help by two-way radio in emergencies.

Training

Since April 1986 when the first Tri-Met bus operators were selected to be light rail operators, the training regimen has been the same. More than 100 operators have gone through the course; about 10 percent washed out in the first 3 weeks—several have been asked to return to bus operation for failure to comply with regulations; some have gone back as a matter of choice. Annual refresher training updates operators' knowledge and skills.

To operate a Tri-Met rail vehicle, employees must be certified by the light rail transportation department after passing the light rail operator's training course—an intensive 3-week program designed to familiarize trainees with various aspects of light rail operation.

Operator trainees complete 1 week of intensive classroom and field instruction, 1 week of main-line training by a qualified instructor, and 1 week of main-line burn-in accompanied by another qualified operator. After this training, operators are expected to have the knowledge and experience to operate a train safely in revenue service and maintain service in varying conditions.

During the first week of training, operator trainees take five written tests, each consisting of 20 questions on the previous day's lecture material. At the end of the second week, trainees take a 100-question final exam, covering daily lectures, standard operating procedures, the *Light Rail Operations Rulebook*, handouts, and practical skills demonstrated by the trainers.

A passing grade is 85 percent; any lower is a failure. Any trainee failing two or more daily exams, a daily and the practical, or the final exam is terminated from the training program and returned to the last position held at Tri-Met (*2*).

TABLE 3 Tri-Met's Five-Year Light Rail Experience

Characteristic	1986-87	1987-88	1988-89	1989-90	1990-91
Line miles	15.1	15.1	15.1	15.1	15.1
Stations	27	27	27	29	30
Transit Centers	5	5	5	5	5
P & R Spaces	1,799	1,799	1,799	1,799	1,799
Actual Expenses	$4,293	$5,439	$5,893	$6,898	$7,412
Transportation	$1,664	$2,020	$2,069	$2,256	$2.309
Maintenance	$2,629	$3,419	$3,824	$4,642	$5.103
Employees	78	101	108	113	124
Transportation	37	47	47	49	49
Maintenance	41	54	61	64	75
Vehicle Miles	70,000	70,000	70,230	71,050	71,000
Ops Cost/Veh Mile	$5.81	$6.49	$6.88	$8.06	$8.91
Revenue Hours	41,232	43,692	43,596	43,584	43,428
Ops Cost/Rev Hr	$90.24	$98.44	$103.80	$120.71	$133.10
Miles/Veh Accident	14,725	19,552	15,606	22,437	20,779
Miles/Pas Accident	6,560	****	21,069	25,837	21,845
Miles/Rail Call	16,999	24,023	52,857	64,115	62,334
Annual Boardings	****	6.6M	6.36M	6.72M	7.44M
Weekday	19,500	19,600	19,700	20,500	23,200
Saturday	****	19,800	16,600	17,400	18,900
Sunday	****	10,000	7,800	9,400	10,500
Weekly	****	128,000	123,000	129,000	145,000
Monthly	****	550,000	530,000	560,000	620,000
Boardings/Serv Hr	****	151.34	145.28	152.88	172.57
Ops Cost/Boarding	****	$0.82	$0.92	$1.04	$1.01
KW hr/Car Miles	8.14	6.49	6.87	6.66	6.97
Avg. Speed (MPH)	15.54	15.17	15.09	14.92	14.94
Pullouts Made	99.95%	100.00%	99.95%	100.00%	99.79
Connect Bus Boardings	27,035	****	****	30,605	****
East Feeder	3,550	****	****	3,777	****
West City	23,485	****	****	26,828	****

**** figures not available

RELATED AREAS

Operational aspects of Tri-Met's 5-year experience with light rail transit treat just a few facets of the effect MAX had on Tri-Met and the region. Much material for other studies lies in the exploration of future expansion of infrastructure and service, economic development, property values, architecture, customer service, marketing, security, and so forth.

Taken as a body, these studies would prove useful to agencies embarking on light rail planning, construction, or service start-up in the near future. Although specific applications of experience must be adjusted for each agency, some generalizations and rules of thumb can be developed that would prove beneficial.

CONCLUSION

In 5 years, Tri-Met's MAX light rail service has gone far beyond what agency officials, political and community leaders, and the general public expected (Table 3):

- Operating experience has been positive, making an increasing contribution to Portland's livability and economic development, and enhancing the transit agency's public image.
- A vote taken in November 1990 was 74 percent affirmative to use property taxes to finance a $125 million bond issue as part of the local match (12.5 percent) to finance a 12-mi extension of MAX service (to the west side of Portland

to Hillsboro) and to fund preliminary engineering of a north-south rail corridor (connecting Clackamas County with the MAX system).

- Nearly $1 billion in public and private development has occurred on or near the MAX line over the last decade.

Hindsight, however, indicates areas in which different decisions would have made the operating experience decidedly more positive:

- An option on 10 cars at 1981 prices was passed up by the agency because it had been negatively affected by an economic recession that caused service cutbacks. Not having the extra cars has constrained improvement of peak-hour schedules to meet passenger demand.
- Vehicle air conditioning was not chosen; some of Portland's hottest days occurred during the summers of 1987 and 1988.
- Single-tracking of LS-I was selected as more economical but schedule frequency is constrained to a maximum of 7-1/2 min.
- A video security system for platforms and facilities was passed up in favor of concession licensing; concessions did not prove profitable at all stations and the necessary presence to deter vandals was not provided.
- A vehicle communication system was retrofitted to allow passengers to communicate with operators in case of emergencies.

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