Assessing the Performance of Portland's New Light Rail Vehicles

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Tri-Met, the transit operator in Portland, Oregon, has recently completed construction of a new light rail system and put into revenue service a fleet of new light rail vehicles (LRVs). Descriptions of the LRV procurement process, the context in which it occurred, and various technical information concerning the LRVs are provided as background. A review of the performance of the LRV fleet during the first 12 months of revenue service is provided. Parameters such as reliability, availability for revenue service, energy consumption, ridership, and operating costs are examined. Particular emphasis is placed on the reliability demonstration plan (RDP)—which Tri-Met is using to monitor LRV reliability—and trends in the RDP numbers are analyzed. A brief comparison of certain productivity measures for Tri-Met bus and light rail operations is made.

THE BANFIELD LIGHT RAIL Transit (LRT) Project is the outgrowth of years of planning to improve the transportation conditions on the rapidly growing East Side of the Portland metropolitan area. It included rebuilding the existing Banfield Freeway and construction of a new LRT line 15.1 mi long from downtown Portland to the suburban community of Gresham.

In the 1970s a proposed freeway in southeast Portland was withdrawn from the Interstate system and the bulk of the funding was made available to support transit corridor projects. Planning studies were started in 1976, and the UMTA alternatives analysis process was completed in 1979 with Banfield as the priority corridor and light rail as the preferred mode. Final design was initiated in 1981. Construction was under way by 1982. The system opened for revenue service in September 1986.

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Because of the freeway rebuilding and use of Interstate transfer funding sources, the overall Banfield LRT Project was managed jointly by the Tri-County Metropolitan Transportation District (Tri-Met) and the Oregon Department of Transportation (ODOT). In general, ODOT was directly responsible for the freeway rebuilding and Tri-Met for the transit portions, although there were many areas of overlap and shared responsibility.

The budget for the overall Banfield LRT Project is approximately $321 million, the transit portion claiming approximately $214 million. The light-rail vehicle (LRV) contract represents approximately 12 percent of the total transit portion. As of June 1988, the project was 99 percent committed and 97 percent expended. Depending upon settlement of claims, the total cost of the project may underrun the budget.

The LRT line encounters a variety of right-of-way (ROW) conditions, including downtown city streets, the median of an existing bridge, a side ROW adjacent to a one-way city arterial, a freeway ROW, a median ROW in a county arterial, and an abandoned railroad ROW. Two-thirds of the line is at-grade with numerous street crossings, and one-third is fully grade-separated adjacent to the Banfield Freeway. There are no subway sections. With minor exceptions, vehicular traffic is not permitted to share the LRT ROW and is physically separated by small curbs and other protective measures. Along the at-grade segments, the LRVs generally either have the opportunity to preempt traffic signals to optimize operations through intersections or have gated protection. For construction purposes, the LRT line was broken into four distinct line sections, eight civil/trackwork contracts, and nine major equipment/facility contracts, including the LRVs.

The downtown Portland segment imposes the majority of ROW and operational constraints found along the whole line. Block lengths are short (normally only 200 ft, property line to property line), thereby limiting overall train length; and streets are narrow (normally 60 ft, property line to property line), thereby requiring tight turning movements. There are also tight vertical and horizontal clearances where the line runs under the ramps and between the piers of two existing bridges. The downtown alignment includes a one-way loop on two adjacent streets.

The steepest grade is approximately 7 percent for 600 ft, and there are several grades of 3 to 5 percent. The minimum horizontal radius is 82 ft and occurs at four locations downtown.

There are 25 stations, yielding an average spacing of 0.6 mi. Station platform length is approximately 200 ft, and platform height (for boarding) is low, approximately 8 in. above the top of the rail at all stations. There are island platforms—left-hand, right-hand, nearside, and farside platforms, depending upon the ROW conditions. A self-service fare collection system with off-vehicle validation and on-vehicle inspection is used. Accessibility for handicapped persons is provided by a wayside lift, which is mounted on each station platform and raises a wheelchair from platform level to LRV floor level. LRT service and bus service are fully integrated, with numerous transfer points and a common fare structure. Five park-and-ride lots were built along the outer half of the line.

LRV PROCUREMENT

Predesign studies, wayside conditions, and operational preferences determined the basic type of vehicle to be procured—a large, articulated, double-sided, double-ended car. In early 1980 Tri-Met, with the assistance of the consulting firm of Louis T. Klauder and Associates, began the process of procuring the LRVs and related equipment and services. Tri-Met sought a procurement that would be competitive, conform to UMTA regulations, and yield an LRV based as much as possible upon proven design. After research of various railcar procurements, Tri-Met elected to use a two-step procurement process.

The first step of the process included issuance of a performance-oriented request for technical proposal (RFTP) by Tri-Met, submittal of technical proposals by interested car builders, evaluation of those proposals, and determination of which proposals were acceptable to Tri-Met. The technical proposals contained no prices or references to prices. The second step included issuance of the invitation for bid (IFB) by Tri-Met to acceptable proposers, submittal of bids, award of the contract by Tri-Met to the lowest bidder, and contract performance.

Before the RFTP was officially released, an extensive industry review was conducted and comments were received from numerous car builders. Four proposals were eventually received, and, after a 4-month evaluation, two were found acceptable. These were from Bombardier of Canada and Siemens of West Germany.

Bids for 26 cars, spare parts, tools, training, etc., were received in May 1981. Bombardier offered the low bid at $775,521 per car for a total amount of $21,662,212, including all incidentals. Contract award was made in September 1981. Contract provisions also allowed for escalation according to Bureau of Labor Statistics indices and specified formulas. During the course of the contract, escalation amounted to an additional $1,363,487 and change orders to approximately $650,000 (or only 3 percent). A separate modification for $650,000 required the car builder to purchase some equipment previously planned as district-furnished-equipment (DFE), raising the total contract to about $24.4 million. Also, Tri-Met supplied other DFE, such as radios, which raised the total cost to approximately $24.7 million.

Bombardier Fabrication Plan

For the Tri-Met contract, Bombardier operated under a license to the Belgian firm of Constructions Ferroviaires et Métalliques, known as BN. BN was the overall designer of the Portland LRV, particularly of the car body structure and trucks. In addition, under separate contracts, BN acted as a subcontractor and supplied Bombardier with certain components such as the truck frames, articulation, door panels, gearbox assemblies, etc. The Portland LRV is basically a stretched and otherwise modified version of the pre-Metro cars built (partially) by BN for Rio de Janeiro in the 1970s. Truck and articulation design were derivative from the Rio car and from other BN designs.

Propulsion system design and supply of hardware were by the BBC-Brown Boveri Company of Switzerland through its North American subsidiary. The Portland traction motor was based on the BBC motor for the Breda LRVs in Cleveland, although there are significant differences. The switched resistor propulsion control system is based on that of certain Swiss railways. Several other components (pantograph, door operators, slewing ring, suspension, etc.) were French or German in design and manufacture, making the Portland LRV very much European in origin.

Major car body subassemblies such as the roof, side walls, and parts of the underframe were fabricated at Bombardier plants in Quebec. Underframe assembly, shell assembly, equipment installation, car wiring, interior finishing, painting, final assembly, and static testing were accomplished at a new Bombardier plant in Barre, Vermont. Trucks were also assembled and wired there.

As previously stated, the contract was awarded in September 1981. Fabrication of the first underframe was started at Barre in autumn 1982 and the first car was moved under its own power in November 1983. Initial proof-of-design testing occurred at the Transportation Test Center (TTC) in Pueblo, Colorado, in early 1984. Table 1 summarizes the major LRV contract milestones.

LRV Description and Performance

The Portland LRV is a six-axle, single articulated car that is double-sided and double-ended. There are four double-wide, low-level doors per side. The car is approximately 89 ft long, 8 ft 8 in. wide, and weighs 90,000 lb (empty). There are 76 seats and room for 90 standees (at 4 passengers/m^2) for a design capacity of 166 passengers. Crush capacity is 256 passengers total. The car is designed for single-unit or multiple-unit operation in consists of up to four LRVs, although revenue operation is limited to two-car trains by the short downtown blocks.

TABLE 1 LRV CONTRACT MILESTONES

September 1980	Request for technical proposals issued
December 1980	Technical proposals received
March 1981	Acceptable proposals determined
May 1981	Bid
September 1981	Contract signed
October 1982	1st underframe fabrication started
December 1982	1st shell assembled
Spring 1983	1st articulation, undercar equipment, and interior equipment installed
June 1983	Carbody compression test performed
Fall 1983	1st trucks installed
November 1983	1st car final assembled
December 1983	Car #101 shipped to TTC for dynamic testing
April 1984	1st car (#103) arrived in Portland via TTC
August 1984	1st car (#102) arrived directly from Barre
Fall 1984	LRV testing started
1985	Delivery and testing
May 1986	1st car accepted, reliability demonstration plan started
October 1986	Last car accepted
Summer 1988	Reliability demonstration plan complete
October 1988	Basic warranty complete

The track gauge is standard 4 ft 8½ in. and the overhead voltage is 750 v dc nominal. The LRV operating range is 525 to 875 v dc. The required minimum horizontal curve radius is 82 ft.

The car body was constructed of low-alloy high-tensile-strength (Corten) steel. The floor structure includes corrugated sheet metal, treated plywood, and rubber flooring. It passed the flammability requirements of a modified ASTM-E119 test. The cushioned seats are on stainless steel frames, and the interior uses melamine-type panels with some fiberglass sections.

The trucks are welded steel structures from BN with rubber suspensions, in-board bearings, one brake disc per axle, and resilient wheels. The primary suspension is a rubber toroid (doughnut) from Clouth, and the secondary suspension is an inverted chevron with alternatively stacked plates of rubber and metal. The resilient wheels are from Penn Machine/Krupp and have a tire and hub separated by rubber blocks in compression to reduce wheel squeal on sharp curves. The center truck is free-wheeling. The motor truck is a mono-motor design with a right-angle drive on each end. A flexible coupling from BBC connects the gear box to the axle. A single race ball bearing slewing ring attaches the motor truck bolster to the car body, while the center truck uses a double race slewing ring to permit both car halves to rotate relative to each other and to the truck.

The BBC traction motor is a four-pole series dc motor with a continuous rating of 198 kW and 280 A at 750 v dc and 1,780 rpm. The motor is self-ventilated. The BBC propulsion control system employs a switched resistor arrangement with contactors controlled by an electronic control unit (ECU). There is no mechanical cam and no regeneration. Parallel operation of the motors is permitted in the two highest motoring positions. A unique feature of the BBC control system is its rate feedback system. The system tries to satisfy the rate request from the master controller handle regardless of vehicle load or wayside conditions (i.e., grades, etc.). Thus there is no explicit load weigh input for normal service propulsion control. Instead the system utilizes the measured vehicle acceleration (deceleration) rate in a feedback loop as an implicit indication of passenger load.

Top speed of the LRV is 55 mph with an overspeed control set at 58 mph. The maximum acceleration rate is 3 mph/sec, and the car reaches 50 mph in about 29 sec.

New York Air Brake provided the friction brake system, which features a spring-applied, hydraulically released disc brake on each axle and track brakes on each truck for use in emergency stops. The disc brake system uses one pump and control valve per truck. These three control units are car-body-mounted under the floor and adjacent to their respective trucks. Service braking is provided by dynamic braking on the motor trucks and supplemental disc braking on the center truck if necessary, that is, for passenger loadings above approximately an AW2 level (i.e., 76 seated plus 90 standees). Emergency braking is provided by disc braking on all trucks, track brakes, and automatic sanding. Spin/slide and jerk limit features are not present during emergency braking. A 4 mph/sec to 6 mph/sec rate, depending on entry speed, is required during emergency braking. Because propulsion (rate) control is effectively disabled during emergency braking, a separate load weigh system is used to modulate emergency brake rate as a function of vehicle load.

The door system is a swing plug design much like that on the General Motors Advance Design Bus with the door operator provided by Faiveley. Dellner provided the fully automatic coupler, which features a cantilever suspension, retractable electric heads, and a self-centering mechanism.

Certain portions of the Banfield LRT line have track circuits and a block signal system with wayside signals protected by an automatic trip stop (ATS) system. The ATS system uses wayside permanent magnets and on-board antennas mounted on the center truck and was provided by Siemens of West Germany. Violation of a red signal automatically brings the LRV to a stop at maximum service brake and indexes a counter.

The Portland LRV also carries a solid state data recorder, purchased separately by Tri-Met and installed by Bombardier, which continuously records certain trainline signals for purposes of testing, operator surveillance, and accident documentation.

RELIABILITY DEMONSTRATION PLAN

During the RFTP process, some consideration was given to life-cycle concerns by including in the LRV contract a requirement known as the reliability demonstration plan (RDP). As the name states, this requirement was an attempt to ensure that, in addition to meeting the traditional criteria for acceptance of cars, the car builder had an obligation to demonstrate the overall reliability of the cars in simulated or actual revenue service after initial acceptance.

The duration of the RDP was set to coincide exactly with the warranty program and runs from start of warranty on the first car until end of warranty on the last car. Individual LRV warranty is 2 years; thus the RDP period is approximately 2½ years, from May 1986 until October 1988.

Recognizing that defining and determining reliability could be complicated, controversial, and possibly counterproductive under the wrong circumstances, Tri-Met sought a simplified approach to the RDP and one in which the car builder would also benefit by its participation and cooperation. Tri-Met's intent also was and is to have a system that is easy to administer and that relies more on common sense and practicality than on theory and literal interpretation. Other more detailed and more scientific approaches might work or might be more appropriate in other circumstances. But the Portland fleet size is small, as are Tri-Met's staff resources for administering the RDP, so increased complexity was just not a possibility. With Bombardier's assistance, the RDP was fully implemented in June 1986 and already has provided much useful information to both parties. The experience has been that about 8 hours of engineering time per week and an equal amount of clerical time are required to administer the RDP.

The primary statistic used to assess reliability is mean distance between failures (MDBF) for the fleet during the RDP period. "Distance" of course is relatively straightforward to record, but "failures" requires some machinations. As described below, data are collected and processed on an ongoing basis, and total fleet mileage is divided by total fleet failures (during the same period) to yield the fleet MDBF. Complicated formulas, computations, data collection, and interpretations have been avoided, yet MDBF seems to be providing a reasonable enough measure of overall reliability to assess major trends and problem areas.

Mileage on each car is read from hub odometers by Tri-Met maintenance personnel on a weekly basis. Under Tri-Met's service plan less than 1 percent of mileage accrued is nonrevenue mileage. Also, accuracy and consistency of the hub odometers have proven sufficient for the RDP purposes. Therefore, little or no massaging of the raw mileage data is required. Since start of revenue service, the 26-car fleet has been operated on average approximately 26,000 mi per week or 1,000 mi per week per LRV. This is about 30 percent higher than estimated in the planning stage and is primarily due to higher ridership than estimated. System mileage as of June 1988 was about 2.5 million.

Concerning failures, the RDP considers any failure relevant for MDBF accounting if revenue service of the offending train is interrupted or delayed by more than 4 min as a direct result of the failure, provided there is no negligence on Tri-Met's part in either operation or maintenance of the equipment. Secondary or follow-on problems are not double-counted. Problems in the storage yard and maintenance facility are counted as relevant failures only if the train is actually entering service. Problems uncovered during normal preventive maintenance checks are not counted. Failures due to "normal" wear-out of components or consumables (e.g., headlights) or due to DFE are also not counted as relevant failures.

Within these general guidelines, Tri-Met and Bombardier have cooperatively worked out a process whereby each recorded problem is reviewed by both parties and mutual agreement is reached as to whether or not the problem is to be counted as a relevant failure for RDP purposes. The important point is that the decision on relevancy of failures is not unilateral on Tri-Met's part but includes consideration by the car builder. Approximately one-third of the problems (trouble tickets) recorded in the system so far have been determined to be relevant failures.

Compilation and processing of all RDP data have been implemented on a local-area network (LAN) of personal computers at the light rail operations facility. A special applications program, known as 3LRV, was developed on the LAN using the GURU software package to record, compute, and output all pertinent RDP parameters. 3LRV was developed to be a hierarchical, menu-driven, user-friendly data base management program.

Mileage and LRV problems (trouble tickets) are input weekly to 3LRV. Each LRV problem is defined by car number, date of occurrence, unique (trouble ticket) number, description of problem, affected system by code in accordance with car builder designations, whether or not the problem is determined to be a relevant failure, and other information related to the warranty program. In turn mileage, failures, and MDBF can be output on an individual car or fleet basis or on a weekly or yearly or cumulative-time basis, or—in the case of failures—can be sorted by system type or trouble ticket number. An example of output is given in Table 2.

Prior to start of revenue service in September 1986, about 120,000 mi had been accrued on the fleet, much of it in testing cars. In addition to the

TABLE 2 WEEKLY OUTPUT FROM 3LRV DATA BASE

MEAN DISTANCE BETWEEN FAILURES 09/10/87

Car	Rel.Fail	R.D.P	Mileage	/Current	M.D.B.F
101	11	52091	65045	09/03/87	4736
102	6	60496	63651	09/03/87	10083
103	10	55696	57882	09/03/87	5570
104	9	52199	52786	09/03/87	5800
105	13	56834	58588	09/03/87	4372
106	15	57953	60993	09/03/87	3864
107	14	58193	60141	09/03/87	4157
108	10	57124	58303	09/03/87	5712
109	10	58576	61778	09/03/87	5858
110	13	56996	61509	09/03/87	4384
111	6	56590	57620	09/03/87	9432
112	11	58484	59606	09/03/87	5317
113	8	55402	56441	09/03/87	6925
114	9	51346	53008	09/03/87	5705
115	11	55665	57532	09/03/87	5060
116	7	59690	62485	09/03/87	8527
117	10	52946	54766	09/03/87	5295
118	8	54508	56601	09/03/87	6814
119	9	61543	63500	09/03/87	6838
120	6	54888	57040	09/03/87	9148
121	5	52104	54480	09/03/87	10421
122	8	57116	58180	09/03/87	7140
123	13	51662	52848	09/03/87	3974
124	6	50809	51257	09/03/87	8468
125	12	55612	57191	09/03/87	4634
126	10	46148	47247	09/03/87	4615
Total:	250	1440671	1500478		5763

Week Mileage : 32450
Week Failures: 1
Week MDBF : 32450

performance testing, as part of the acceptance program each LRV was operated approximately 1,500 mi in a burn-in cycle that simulated revenue service and repetitively exercised most of the car systems. Mileage and failures during testing and burn-in were not included in RDP calculations, and the burn-in process was used to help identify and correct "infant mortality" and other problems not uncovered during the inspection process. About 70,000 mi of the total prerevenue service mileage was actually RDP mileage. The initial failure rate, despite the burn-in program, was reasonably high and a cause of concern to Tri-Met.

Figure 1 shows the cumulative MDBF from the beginning of the RDP in May 1986 through September 1987. It is evident from Figure 1 that there has been a significant improvement in reliability since the cars were first put into revenue service; cumulative MDBF nearly trebled, from approximately 2,000

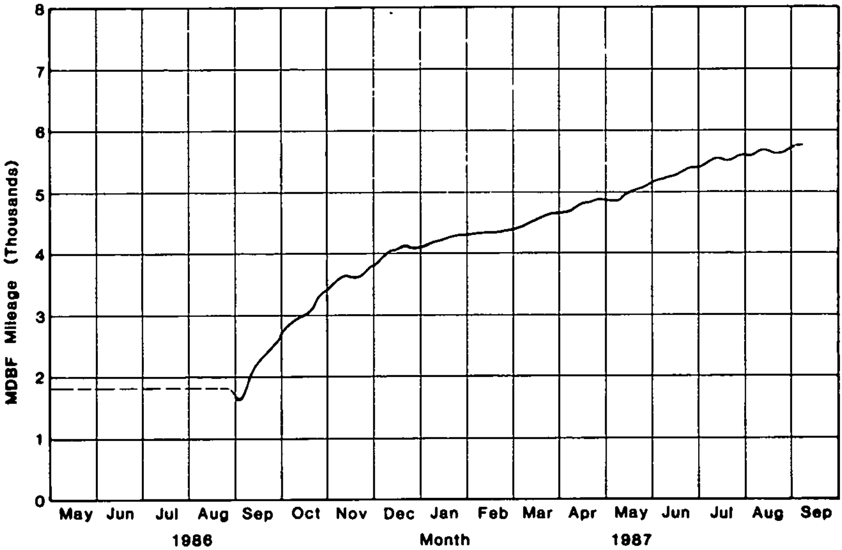

FIGURE 1 Cumulative mean-distance-between-failures data.

to almost 6,000 mi in about 12 months. As of early September 1987, the cumulative MDBF was 5,763 or an average of one failure approximately every day and a half. Figure 2 also shows the cumulative MDBF, first from the start of revenue service and second from January 1987, thereby discounting the higher failure rates present in the very beginning of the RDP program (e.g., summer 1986). For these time periods MDBF has been 6,323 and 7,523, respectively, which corresponds to about four relevant failures a week or every 26,000 mi. By June 1988, cumulative MDBF had risen to approximately 7,600, while MDBF for calendar year 1988 through June was in excess of 15,000. Figure 3 shows the monthly (noncumulative) MDBF through September 1987 and also portrays the improvement in a more aggregated way.

These data show that approximately 12 percent of the relevant failures through September 1987 occurred during the first 4 months or, using mileage as a measure, the first 4 percent of the RDP. The improvement in MDBF is a direct function of the car builder's modification program, which in turn is in response to collection and presentation of reliability data. Bombardier and Tri-Met have established an MDBF objective of 7,500 mi at the end of the RDP. On the basis of trends established to date and discounting the higher incidence of failures in the first few months, it appears that this goal will be achieved. In fact, discounting the first 4 months, the 7,500-mi objective will probably be well exceeded.

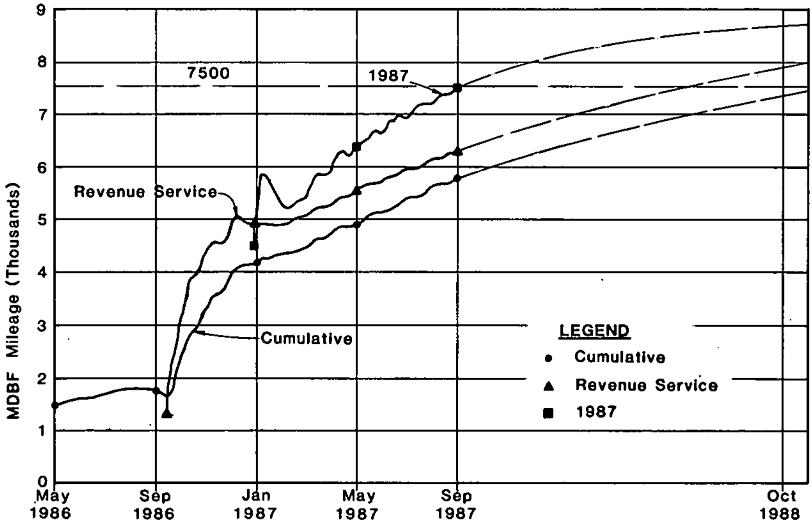

FIGURE 2 Cumulative and revenue service MDBF data.

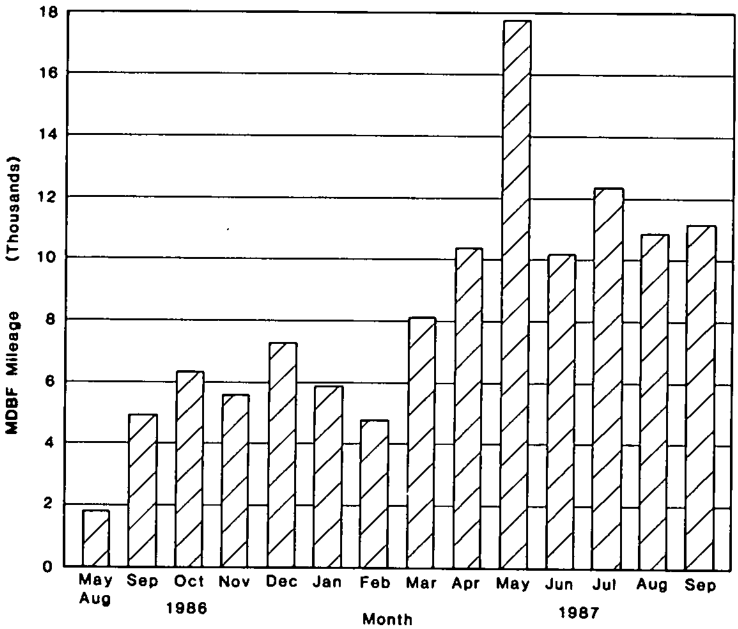

FIGURE 3 Monthly MDBF (noncumulative).

In effect the RDP has served as a management information system. For example, Figure 4 provides a breakdown of the total number of all trouble tickets and relevant failures for each major system in the car, thereby helping to establish priorities for change. Problems with the friction brake and propulsion systems have resulted in the highest incidence of relevant failures. Accordingly four major fleetwide modification programs have been implemented that have resulted in reduction in brake and motor failures and contributed to the improvement in MDBF.

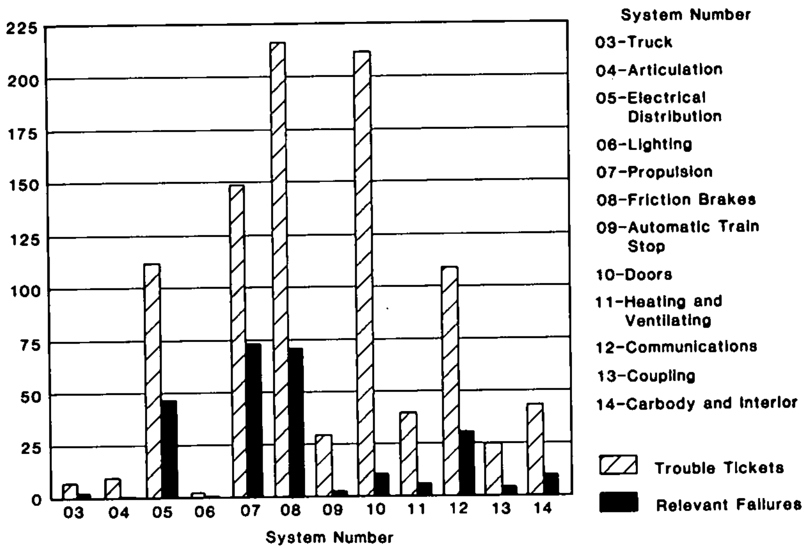

FIGURE 4 Failures per system.

Had time and resources allowed and with hindsight as a guide, Tri-Met's experience is that it would have been desirable to extend the burn-in mileage to at least 5,000 mi per car prior to acceptance to more thoroughly exorcise the early problems. Initially the Portland LRV was not as proven a design as Tri-Met had intended from the RFTP process. Many critical systems, such as the friction brakes and doors, were derived from earlier designs but had not actually been used before in the exact Portland configuration. The propulsion supplier and the friction brake supplier had not worked together before, and the critical propulsion/brake interface required substantial development. The car builder's assembly plant was essentially a new plant experiencing its own learning curve. The result of these factors was a relatively high incidence of problems as the trains first began to accrue mileage. The improvement in MDBF is a tribute to the diligence of both the car builder's and Tri-Met's staffs in identifying, troubleshooting, and correcting problems on both an ad hoc and a systematic basis.

Another indication of reliability of the cars is availability of cars for revenue service. Tri-Met routinely schedules 22 of its 26 car fleet for revenue service in the peak periods. To date this availability has always been met. In fact, maintenance statistics indicate that actual availability has averaged about 90 percent gross (regardless of reason of unavailability) or about 96 percent net (excluding routine maintenance checks).

ENERGY CONSUMPTION

Availability, consumption, and cost of energy are of vital concern to every public transit agency, particularly since the energy shortages in the 1970s. Accordingly Tri-Met established a contractual requirement for LRV energy consumption and specified a particular set of test conditions for demonstrating compliance. After a review of specifications for other transit vehicles, the requirement for energy consumption was set at 7 kilowatt hours (kwhr) per car mile, and the test conditions included an empty car with a test crew and instrumentation (AWO+), new wheels, level tangent track, a 1-mile trip repeated 10 times and averaged using a duty cycle of full acceleration from a stop to maximum speed of 55 mph, maintenance of 55 mph, full deceleration to a stop, and a 30-sec dwell with all auxiliaries running.

Testing at TTC showed that the energy consumption under these conditions was approximately 4 percent higher than allowed by contract but was considered acceptable within the accuracy of the tests. Further substantiation onsite in Portland was never accomplished, because of ROW conditions (e.g., grades and curves) and operational constraints from the signal system.

However, since start of revenue service Tri-Met has elected to undertake a program to monitor carefully the energy consumption of the system in actual operation. Prior to 1986, it was thought that all the ROW conditions (curves, grades, traffic lights, etc.), passenger loadings, wheel wear, and traction duty cycles of actual operations would contribute to a significantly higher energy consumption than seen under the test conditions. Early planning studies and cost estimates were based on a conservatively high energy consumption rate of 9 kwhr/car mile in actual operation on the Portland system. It was considered impractical to try to instrument a car in revenue service and measure direct energy usage during operation. Furthermore, without great effort the sample set of data would be small. Therefore Tri-Met decided to monitor the kilowatt hours directly from the meters of the utility companies in each of the 14 traction substations on the system. By coordinating the monitoring of the kilowatt hours and the car mileage into the same time period, it has been relatively easy to develop an empirical kwhr/car-mile statistic for actual operation of the fleet as a whole.

The average value since start of revenue service is 7 kwhr/car mile and, in addition to direct traction energy of the LRVs on the mainline, this includes substation losses, overhead line losses, and energy consumption from LRV storage in the storage yard. Passenger station power, maintenance building power, and signal power, in addition to energy of construction (technical, social, or otherwise), are not included. Substation losses have been calculated to be approximately 0.3 kwhr/car mile; overhead line losses, 0.1 kwhr/car mile; and LRV storage, the equivalent of 0.1 kwhr/car mile, making the effective or actual energy consumption at the point of usage about 6.5 kwhr/car mile. At 166 places per vehicle, this figure translates to 0.04 kwhr/place mile. No attempt is made here to trace the energy consumption numbers back to the source or generation of the electricity. However, in the Portland area much of the electricity is generated by hydropower, and average inefficiencies for converting oil or coal into electric power are not applicable in this environment.

A brief comparison of these data with those of Tri-Met's bus fleet shows a significant lower energy consumption for LRV when viewed on a per-place-mile basis. For example, based on a composite average of Tri-Met's bus fleet, the fuel consumption is about 4.1 mi per gallon in operation and the average capacity (number of places including seating and standees) is 73. Using an energy equivalence of 40.7 kwhr per gallon of diesel fuel (*1*), the average Tri-Met bus consumes about 10 kwhr/bus mile or 0.14 kwhr/place mile. This information is summarized in Table 3.

TABLE 3 CONSUMPTION OF FUEL, LRV VERSUS BUS

	LRV	Bus
Number of places per vehicle	166	73 (average)
Energy consumption		
Per vehicle mile	6.5 kwhr/car mile	0.24 gal/bus mile = 9.93 kwhr/bus mile
Per place mile	0.04 kwhr	0.14 kwhr

To repeat, these data represent energy consumption at point of usage, are composite averages for the bus, and are based on actual operation of the rail and bus fleets. In summary the data provide evidence for the proposition that, on a place-mile basis, the energy consumption of the LRV is only about one-third that of the bus as used in actual operation on the Tri-Met system.

PRODUCTIVITY

Table 4 provides a list of certain fundamental parameters describing Tri-Met's LRT and bus fleets and their respective utilizations. As in any analysis of aggregate numbers, care should first be taken in assessing the comparability of the data. Definition of terms can also often significantly influence the conclusions reached. An attempt has been made here to develop and compare similar terms, recognizing that original data are not always collected with end results in mind.

TABLE 4 COMPARATIVE OPERATING PARAMETERS

	LRV	Bus
Boarding passengers (daily)	19,700 (12%)	149,800 (88%)
Number of vehicles	26 (4%)	603 (96%)
Fleet mileage (annual $\times 10^6$)	1.3 (6%)	21.6 (94%)
Mileage per vehicle per day (full annualization)	135	100
System speed (mph)	15.7	14.0
Schedule speed (mph)	20.1	N/A
Number of transportation employees	46	978
Number of maintenance employees	53	283
Transportation employees per vehicle	1.77	1.62
Maintenance employees per vehicle	2.04	0.47
Operations employees per vehicle	3.81	2.09
Operations employees per vehicle mile ($\times 10^{-6}$)	76.1	58.4
Operations employee per place mile ($\times 10^{-6}$)	0.46	0.80
Operations employees per boarding passengers ($\times 10^{-3}$)	5.0	8.4

Daily boarding passengers are averages for the fiscal year (July 1986 to June 1987) or for the rail from September 1986. Slightly higher than average LRV ridership occurred in the first 3 months of revenue service, but recent trends in the spring and summer of 1987 indicate a return to the yearly average. These data indicate that on the basis of boarding passengers, the LRT system carries approximately 12 percent of Tri-Met's patronage with the following:

- 4 percent of the total vehicle fleet,
- 9 percent of the total capacity in places (seated plus standees),

- 6 percent of the total fleet mileage, and
- 12 percent of the total fleet capacity in place miles.

Good data are not yet readily available describing trip characteristics, especially trip length; therefore comparison of system utilization on the per-passenger-mile basis cannot be made.

System speed incorporates layovers, turnbacks, etc., and is a constructed rather than an empirical number. The LRV system speed is about 12 percent higher than that of the bus. Actual schedule speed for the LRV is about 20 mph or about 1 to 2 mph lower than estimated in the planning phases. Tri-Met is investigating ways to improve the travel speed, particularly in certain portions of the alignment where traffic signals in the reverse direction of a prior one-way street need further optimization.

During the first 12 months of LRV revenue service Tri-Met has been operating its LRV fleet approximately 30 percent more than estimated because of higher-than-anticipated ridership. This usage level is also reflected in the daily mileage per vehicle, with the LRV logging approximately 35 percent more than the average bus.

Another interesting comparison is the number of employees required to provide the various measures of service. In its operations division, which is charged with providing the actual transit service, Tri-Met is organized into maintenance and transportation departments both for bus and for rail. In this analysis, the transportation employees include vehicle operators, road supervisors, dispatchers, and administrative and clerical employees, while the maintenance employees are mechanics, foremen, cleaners, administrative and clerical employees, and—in the case of rail—all ROW (track, traction power, signal, etc.) maintenance staff. Planning, engineering, finance, and community relations staff are not included in either case.

From Table 4 it is seen that the number of transportation employees per vehicle is slightly higher for the LRV compared with the bus. Maintenance employees per vehicle is significantly higher—by about four times. Concerning the former, it is somewhat surprising that the LRV is not lower, given the ability to operate in multiple-unit (MU) consists in the peak hours with only one train operator. However, reverse economies of scale enter into the picture in that the rail dispatch and control center, which is separate from the bus, requires a minimum or threshold number of employees to maintain a similar 24-hr-a-day, seven-day-a-week operation. Concerning the latter, obviously the more complicated rolling stock and all the extra ROW infrastructure contribute to the much higher ratio of maintenance employees for rail.

On a per-vehicle basis, the rail system requires almost twice as many employees (transportation and maintenance) as the bus, while on a vehicle-mile basis the rail system needs only about one-third more employees.

However, using the statistic of employees per place mile, and considering the relatively higher capacity of large articulated LRVs, one sees that the LRT system requires only about half the work force of the bus. Similarly the LRT system is more productive on the basis of employees per boarding passenger, about 5.0 versus 8.4 ($\times 10^{-3}$). No attempt has been made here to try to sort out or assign factors to the feeder bus network supporting the rail line, or vice versa. Statistics are based on aggregate totals and reflect only how the equipment is utilized.

The comparative statistics developed to date appear to support the contention that an LRT system with large MU vehicles and modest ROW infrastructure can provide a more productive and more efficient transit service than buses. However, the extent to which the "newness" of the LRT system, the advantages of warranty, the concentration of travel into a corridor, the particular conditions in Portland, etc., affect productivity is not known and clearly beyond the scope of this paper. Caution should be taken in extrapolating a limited situation into a generalization applicable to any other environment. Nevertheless Tri-Met's LRT experience to date has generally been a positive one that seems to offer promise for the future. As constructed and operated in Portland, the LRT mode gives an indication of the relative productivity in transit service.

SUMMARY AND CONCLUSIONS

As part of its LRV procurement, Tri-Met has implemented a reliability demonstration plan to identify, quantify, prove, and improve the reliability of the cars in revenue service operation. The resultant RDP is simple to administer, is concurrent with the warranty period, relies on the MDBF statistic as an indicator, is implemented on a computer network, and requires the cooperation of the car builder. Mileage and trouble tickets are recorded weekly, and determination of relevant failures that affect revenue service is accomplished mutually by Tri-Met and the car builder. MDBF has improved significantly since the beginning of the program and ranges between approximately 6,000 and 8,000 depending on the exact definition. Recent MDBF has been in excess of 15,000. Based on current trends it appears that the contractual goal of 7,500 cumulative will be exceeded by the end of the RDP period. The improvement in MDBF is attributed in part to the systematic identification of problems through the RDP.

A program for monitoring energy consumption has also been implemented by Tri-Met. Meters at traction substations are read directly on a weekly basis, and the average energy consumption is 7 kwhr/car mile at the substations or 6.5 kwhr/car mile at the point of usage, the train. These values are approximately one-third the average energy consumption of Tri-Met's bus fleet.

A comparison of certain productivity measures for Tri-Met's LRT and bus operations has been made, recognizing the difficulties in getting truly comparative data. The increased maintenance requirements of the LRT system, particularly for ROW infrastructure, appear to be offset by the higher capacity and utilization of the LRVs. Number of employees per place mile of service provided by LRT is slightly more than half that by buses.

Conclusions from this effort are as follows:

- A reliability demonstration plan is a very useful tool as part of a rail car procurement;
- MDBF is a useful statistic, provided confusion of terms can be eliminated;
- Early failures can be discounted in arriving at the steady-state level of reliability;
- The reliability of the Portland LRV is quite satisfactory and likely to meet contractual objectives by the end of the RDP period;
- The LRVs have substantially lower energy consumption than buses; and
- The LRT system as implemented in Portland appears to offer better productivity than do buses.

REFERENCE

1. F. Fiels. *Comparative Energy Costs of Urban Transportation Systems.* Princeton University, Princeton, N.J., 1974.