Chapter 5

OPERATIONAL EXPERIENCE

INTRODUCTION

The advocates of automatic train control advance three general arguments to support their case-safety, performance, and cost.

An automated system, they contend, has a higher level of safety than one in which the basic controlling element is the human operator, Automatic devices function with a consistency and repeatability that man simply cannot match. In a well-designed automatic system. hazardous events are precluded by the engineering of the system; and if an automated device should fail, there are other design features to assure that the system will revert to a condition known to be safe (the “fail-safe” principle). In short, because the behavior of machines is predictable, contingencies can be foreseen and compensated for in the design. The human operator, by contrast, is not as predictable. Man is prone to errors of judgment, inattention, fatigue, and other frailties. Furthermore, the human operator takes longer to process information and to respond, with the danger that he may not do so correctly. And so, the argument runs, the automated device should be preferred over the human because it leads to a system of greater inherent safety.

The second argument is that an automated train control system leads to superior performance. Here, the argument rests on the superiority of machine over human capabilities, Automated devices work rapidly, with greater precision, and in a manner always consistent with the objectives of the system. In the case of computers, they have a recognized advantage over man in their ability to process, store, and retrieve large amounts of information and to apply this information in the solution of complex problems. Thus, an automated train control system can move traffic at higher speeds and on closer headways; and-equally important—it can make rapid compensations and adjustments in response to changing conditions.

Automated train control systems are also asserted to be less expensive than manual systems in the long run. The initial capital costs of an automated system are admittedly higher, simply because there is more equipment to design and build, It is claimed, however, that these costs are more than offset by the reduced operating expenses of an automated system. Automated systems are cheaper to run because they have fewer operators, and it is labor costs that represent the bulk of operating expense, Automation can also produce other savings. An automated system is claimed to be more economical in its energy use because the equipment is operated at optimal speeds and acceleration-decelcration profiles. This leads to a second form of economy. less wear and tear on the equipment due to improper operation. Finally, the optimum mode of operation brought about by automation supposedly leads to a more efficient system, making it possible to provide the same amount of passenger service with less rolling stock.

All of these assertions about the safety, performance, and cost advantages of automated systems are subject to question. The purpose here, however, is not to enter into debate. Instead, the arguments advanced for automation will be treated as hypotheses, to be tested by the empirical evidence and operating experience of transit systems where various automated control features are in use. The aim is to look at the operational record to see if there are differences among transit systems which are attributable to the level of automation. The discussion is presented as a series of propositions or issues, grouped under the general headings of safety, performance, and cost. As a corollary, an examination is also made of the role and effectiveness of man in systems with different levels of automation.

SAFETY

Safety has two aspects. There is the immediate question of passenger accidents and injuries which may be attributable to some aspect of automated train control. There is also the question of the inherent safety of the system, i.e., the extent to which the design of the system helps prevent accidents. The first question has to do with the narrower, historical concern of whether accidents have occurred, while the second deals with the larger topic of safeguards incorporated in the design against possible future accidents.

Allied to these questions is the matter of passenger security. Automated systems, with fewer transit property employees on board the trains and in the stations, might be assumed to offer the passenger less protection from assault, robbery, and other criminal actions. This point needs to be examined first because of its implications for public safety and, second, because of its influence on the decision to replace humans with automated devices in other, future, transit systems.

ISSUE O-1: TRAIN PROTECTION

Are automatic train protection (ATP) devices more effective, and inherently safer, than manual train protection methods?

The experience of the transit industry indicates clearly that ATP provides a surer method of train protection, and all new systems now under development will employ ATP in preference to manual means.

Train protection involves three basic control functions: train separation, overspeed protection, and route interlocking. In a manual system, these functions are performed by the train operator who maintains visual observation of the track ahead and runs the train in conformance with established rules and procedures. When these functions are automated, there are mechanical devices and electrical circuits at the wayside and on the train itself to assure that proper following distance is maintained (train separation), that train speed does not exceed that required for safe stopping or negotiating curves (overspeed protection), and that conflicting moves along the lines or through switches are prevented (route interlocking).

The degree of automation and sophistication of control varies from system to system. In the simplest form, ATP is accomplished by automatic wayside block signals and mechanical trip stops that activate the emergency brakes for any train entering a block illegally or exceeding the allowed speed. At higher levels of automation, train movement is regulated continuously to maintain safe speed, following distance, and routing.

Train control engineers and transit properties universally consider ATP to be the first and basic method of preventing collisions and derailments. The newer systems built and those now under construction all incorporate fully automatic train protection mechanisms, Older properties (such as NYCTA, CTA, and MBTA) have long had wayside signals with trip stops to provide ATP, but they are installing fully automated cab signal equipment as they build new lines or modernize the existing lines. Table 8 is a summary of ATP provisions in existing and planned transit systems.

The operating experience of existing transit systems with automatic train protection devices at-

TABLE 8.—Train Protection Methods in Existing and Planned Transit Systems

TRANSIT SYSTEM	TRAIN SEPARATION	OVERSPEED PROTECTION
Existing Systems:		
BART (San Francisco)	Automatic, with advisory cab signals	Automatic, with advisory cab signals
CTA (Chicago)	Mixture, converting to cab signals[1]	Mixture of manual, trip stops with timers, and cab signals
CTS (Cleveland)	Airport Ext. automatic trip stops on rest	Airport Ext. automatic trip stops with timers on rest
Dallas-Ft. Worth Airport	Automatic	Automatic
MBTA (Boston)	Red Line Ext. automatic, trip stops on rest	Red Line Ext. automatic, manual on rest
NYCTA (New York)	Wayside signals with trip stops[2]	Trip stops with timers
PATCO (Lindenwold Line)	Automatic, with advisory cab signals	Automatic, with advisory cab signals
Seattle-Tacoma Airport	Automatic	Automatic
In Planning/Construction:		
MARTA (Atlanta)	Automatic, with advisory cab signals	Automatic, with advisory cab signals
MTA (Baltimore)	Automatic, with advisory cab signals	Automatic, with advisory cab signals
WMATA (Washington, DC.)	Automatic, with advisory cab signals	Automatic, with advisory cab signals

[1]Present system is a mixture of no signals, wayside signals with trip stops, and cab signals with automatic stop enforcement.
[2]Conversion to cab signals is planned for new lines and extensions.

tests to the general effectiveness and reliability of such equipment. PATCO, AIRTRANS, and SEA-TAC have never had a collision or derailment in passenger service attributable to malfunction of ATP equipment, BART has had one ATP accident, In 1972, shortly after inauguration of service, a train ran off the end of the track at the Fremont Station. The cause of the accident was traced to a faulty crystal oscillator in the carborne speed control electronics, causing the train to speed up when it should have slowed to enter the station. A redundant speed control circuit has been added to prevent recurrence of such a mishap and there have been no other accidents related to ATP in the succeeding three years of passenger service.[40]

The most frequent types of accidents in a manual train protection system are the result of one train following another too closely, misjudging stopping distance, exceeding safe speed on curves, or entering improperly alined switches. All are products of human error. ATP is specifically designed to prevent these types of accidents by interposing automatic safeguards to keep trains properly spaced and running at a safe speed on the correct route, regardless of human error or inattention. The safety record of rail rapid transit owes much to the effectiveness of such automatic protective devices which apply the fail-safe principle to assure that the train will maintain a known safe condition in the event an automated element malfunctions.

[40]The collision between a BART test train and a maintenance vehicle in January 1975 occurred at night on a weekend, when the system was shut down. The cause was found to be human error and improper operating procedure by the maintenance vehicle driver and the train supervisor in central control.

The operating experience of the Chicago Transit Authority over the past 10 years offers an instructive example of the safety advantages of automatic over manual train protection methods. The case of CTA is singled out because it is typical of the operating experience that has led existing transit systems to conclude that ATP is a necessity.

CTA can be characterized as a mixed system. Ten years ago CTA had wayside signals with trip stops on some lines or parts of lines and no signal protection on the remainder. In the unsignaled portion of the system the safety of train operation depended solely on the alertness of the motorman and compliance with operating rules designed to prevent collisions and derailments, As the new Dan Ryan and Kennedy extensions were built, they were equipped with cab signals and automatic overspeed protection, In some cases, however, these new lines merged with older portions of the system having either no signals or wayside signals with trip stops. Beginning in 1965, CTA undertook a modernization program, part of which involved installation of cab signaling to protect segments of trackage formerly not signaled. This work is now nearing completion, but in late 1975 the system remained a mixture of wayside and cab signals, with a few sections still not signaled at all. A train operator on the North-South line or the West-Northwest line, for example, runs the train under all three forms of train protection at one time or another during the course of a single trip.

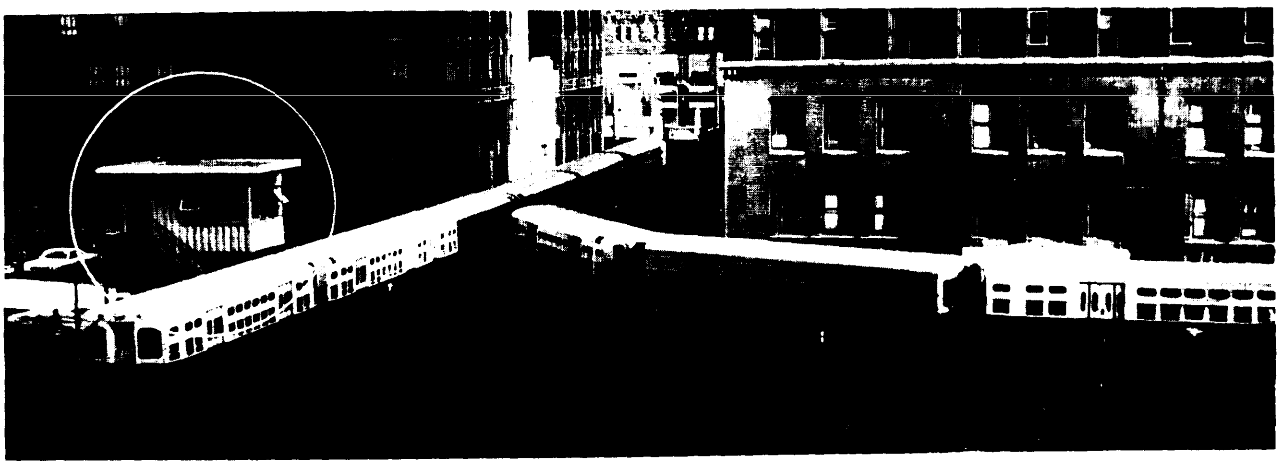

FIGURE 47.—Interlocking Control Tower for Train Protection

The record of collisions and derailments from 1965 to 1974 illustrates the consequences of operating under incomplete signal protection or by manual and procedural methods alone. There were 35 collisions and 52 derailments in this period, an average of about one accident every 6 weeks. Most were minor accidents, but there were two fatalities—both in a 1966 derailment produced by equipment falling off the train. An analysis of accident causes (Table 9) shows that human error was a contributing factor in every collision and in almost two-thirds of the derailments.[41] Collisions typically resulted from the train operator misjudging stopping distance or following too closely. Derailments were most often caused by overspeed on curves or by the operator entering an improperly alined switch while proceeding on hand signals.

The record also shows that cab-signaled ATP was a contributing factor in only one accident. In this case, the motorman was operating in cab-signal territory for the first time on the first day of operation of a newly extended line. The cab signaling unit had not cut in as the train passed from unsignaled into cab-signaled territory, and not noticing this, the motorman failed to operate accordingly.[42] The train rounded a curve in the subway and hit a standing train ahead because the motorman was unable to stop in time. CTA determined the cause of the accident to be a combination of cab signal equipment failure and human error. CTA has taken measures to prevent recurrence by tighter instructions, modification of procedures for entering cab signal territory, and more conservative turn-on and testing procedures when initiating service with new cab signal equipment.

Two points emerge from this analysis. First, ATP is superior to manual methods of train protection because it safeguards against most types of human error, which cause the majority of collisions and derailments.[43] Second, a mixture of signaled and unsignaled lines requires two distinctly different (and perhaps incompatible) modes of response from the train operator, with the attendant risk of confusion between the two at a critical moment.[44] Both these points were recognized by CTA, which cited prevention of accidents resulting from human error and attainment of a uniform level of signal protection for the whole system as prime reasons for undertaking the cab signal conversion program.

[41] Apart from human error, the greatest contributing cause in derailments was car defects (16 of 52 cases).

[42] CTA procedures prescribe that, in this circumstance, the motorman should continue to operate under manual rules and be prepared to stop within line-of-sight distance,

[43] No automatic system is foolproof. After the collision of trains in the Mexico City transit system on October 20, 1975, in which 27 people were killed, the investigation disclosed that the train operator (in violation of established rules) had disconnected ATP equipment that would normally have stopped the train.

[44] In a different way, the recent collision in Boston illustrates the risk associated with mixing manual and automatic methods of train protection, On August 1, 1975, in the tunnel between the Charles Street and Park Street stations, an MBTA Red Line train was struck from the rear by a following train. About 2 minutes later, the second train was hit by a third entering the tunnel. There were no fatalities, but 130 were reported injured. This part of the Red Line is protected by wayside signals and trip stops. However, about an hour before the accident, a trip stop had malfunctioned; and trains were being moved past the trip stop under manual rules requiring that the motorman proceed slowly and be prepared to stop within line-of-sight distance. The exact cause of the accident has not been officially determined, but it seems to have resulted not from a failure of the ATP system but from a lapse in the manual back-up procedure, This suggests that a transit system becomes vulnerable to human error at a time when the normal automatic protection methods are inoperative and train operators must revert to unaccustomed manual and procedural methods.

TABLE 9.—Analysis of CTA Accident Record, 1965–74

		CONTRIBUTING FACTORS*						
TYPE OF ACCIDENT	TOTAL	Car Defect	Track Defect	Weather	Wayside Signals	Cab Signals	Human Error	Vandals
Collision	35	5	0	2	1	1	35	3
Derailment	52	16	4	0	6	0	31	1

● Some accidents had more than one contributing factor.

ISSUE O–2: TRAIN OPERATION

Does automatic train operation (ATO) have an influence on safety, as measured by the type and number of passenger injuries?

Based on analysis of the records of four representative transit systems, there is no difference in the injury rates between manual and automatic modes of train operation. Passenger inexperience is more of a causal factor than the mode of operation.

There are two types of passenger accidents that might be influenced by automatic train operation—falls on board due to train motion and door closure accidents. If either automatic or manual train operation resulted in a characteristically smoother ride, the frequency of passenger falls and injuries due to lurching of the train during starts, stops, and running on curves would be expected to be lower. Automatic door operation might be expected to produce more instances of passengers being struck or caught by closing doors because there is no train attendant to regulate door operation for the tardy or unwary passenger,

An analysis of accident records for four representative transit systems (NYCTA, CTA, PATCO, and BART) does not substantiate either of these hypotheses. The frequency of train motion accidents in the NYCTA and CTA systems, where trains are run manually by a motorman, is essentially the same as in PATCO and BART, where train operation is automatic under the supervision of an operator in the control cab. Similarly, the rate of door closure accidents does not differ regardless of whether doors are operated manually (either by a conductor or train operator) or automatically. (See table 10.)

A word of caution must be given regarding transit passenger injury statistics. There are no common definitions of injury (or its causes) employed by the four systems considered here or by the transit industry as a whole. For this reason, the injury rates for various kinds of accidents are not precisely comparable from system to system and should be taken only as general indications of the safety record. It should also be noted that the figures given are for claimed injuries, i.e., passenger reports of injury at the time of the accident without regard to severity or substantiation by medical examination. The number of actual injuries (e.g., those requiring medical treatment or those that lead to a later claim for compensation) is considerably lower, perhaps by as much as half.

It must also be emphasized that passenger injuries due to any aspect of train operation are events of extremely low frequency—literally about one in a million. By far, the greater proportion of injuries to transit system patrons (60–80 percent of all accidents) occurs in stations. Falls on stairways, for example, typically account for more injuries than all types of train accidents combined. Table 11, a summary of passenger accident statistics in four systems, illustrates the general nature of the rail rapid transit safety record.

With regard to fatalities, rail rapid transit is one of the safest of all modes of transportation. In 1973, 15 people lost their lives in rail rapid transit acci-

TABLE 10.—Passenger Injuries Due to Train Operation

TRANSIT SYSTEM	TRAIN MOTION		DOOR CLOSURE	
	Mode of Operation	Rate[1]	Mode of Operation	Rate[1]
BART (1974)	Alltomatic	[2]1.0	Automatic	1.6
CTA (1973)	Manual	0.7	Conductor	1.3
NYCTA (1973/74)	Manual	0.4	Conductor	0.4
PATCO (1973)	Automatic	0.6	Train Operator	1.4

[1] Reported injuries per million passengers.

[2] The BART figure is for all on-board accidents, which include falls due to train motion and other types of mishaps. The rate of accidents due to train motion alone is therefore somewhat lower, probably about the same as the other systems.

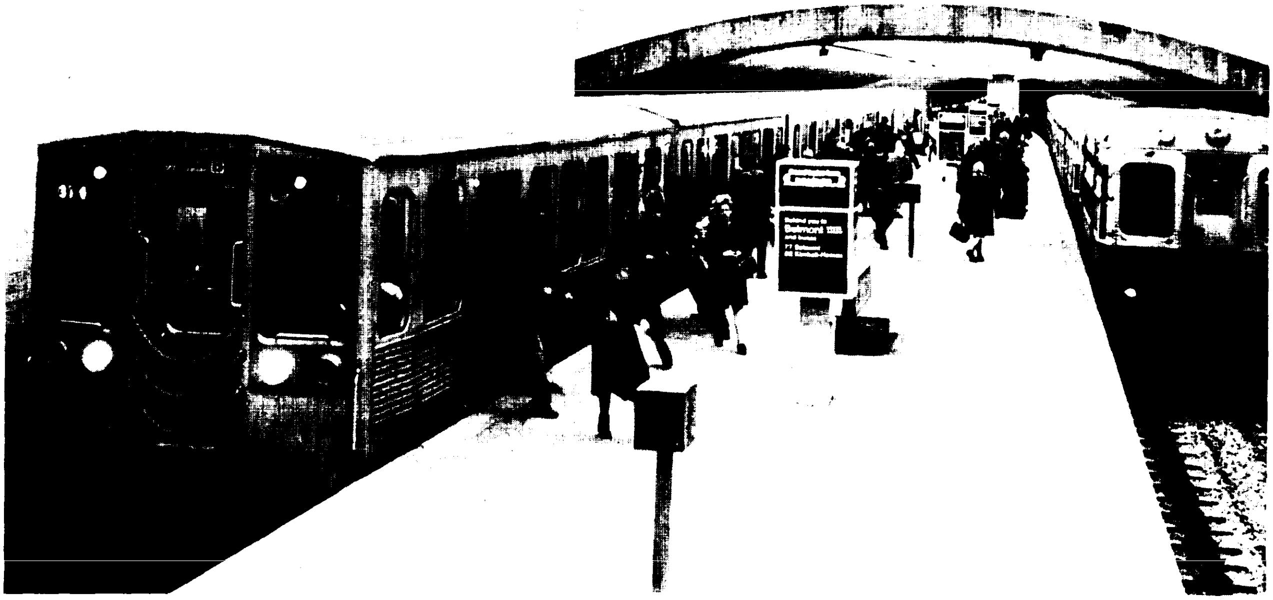

FIGURE 48.-CTA Passengers Alighting at Belmont Station

TABLE Il.—Passenger Accident Summary

TYPE OF INJURY	BART (1972-74)		CTA (1969-73)		PATCO (1969-73)		NYCTA (1973–74)	
	Rate[1]	Percent	Rate[1]	Percent	Rate[1]	Percent	Rate[1]	Percent
STATIONS							3.4	61
Falls on Stairs.	24.1	61	3.3	24	3.1	21	NA	[2] –
Gates/Turnstiles.	NA	[2] –	0.2	1	2.0	14	NA	[2] –
All Other	8.5	21	7.2	52	4.4	30	NA	[2] –
TRAINS								
Boarding/Alighting.	1.3	3	0.7	5	0.7	5	0.4	7
Doors.	3.8	10	1.2	9	1.8	12	0.4	7
Train Motion.	1.4	4	0.8	6	0.9	6	0.4	7
All Other.	0.3	1	0.4	3	1.6	11	1.0	18
TOTAL.	39.4		13.8		14.5		5.6	

[1]Reported injuries per 1 million passengers.
[2]Not available.

dents[45]--a rate of 0.0075 fatalities per million passengers. Fatality data for other modes of transportation during 1973 are shown in table 12.

Rail rapid transit ranks among the safest of transportation modes in terms of fatality rate, as well as in absolute numbers. In the period 1970–72, the rate was 0.83 deaths per billion passenger-miles in rail rapid transit,[46] as compared to 0.69 in transit buses, 1.03 in scheduled air carriers, 2.6 in passenger railroads, 20,8 in private motor vehicles, and 21.1 in elevators (Battelle, 1975), To set the rail rapid transit fatality rate in additional perspective, the figure of 0.83 per billion passenger-miles is the equivalent of a six-car train, carrying a total of 900 passengers, traveling over 53 times around the earth before a death occurs.

Of the passenger deaths in rail rapid transit, about 80 percent are the result of falling while walking between cars on a train in motion. The re-

[45]There were also 94 deaths due to suicide jumps from station platforms or trespassing on the right-of-way.
[46]Excludes suicides and trespasser deaths.

TABLE 12.—Fatalities in the United States by Transportation Mode During 1973

TRANSPORTATION MODE	NUMBER OF DEATHS
Private Auto	33,500
Trucks	5,700
Motorcycle/Motor Bike	3,130
Marine, recreational	1,754
Marine, commercial	320
Aviation, private	1,340
Aviation, commercial	227
Grade Crossing	1,215
All Railroads	698
Taxicabs	170
Buses	170
Pipeline	70
Rail Rapid Transit, passengers	15
Rail Rapid Transit, suicides and trespassers	94

SOURCES: New York City Council on Economic Environment, 1974; and National Safety Council, 1974.

mainder are produced by a variety of causes, no one of which accounts for a significant proportion. Thus, train control (either manual or automated) is a contributory factor in only a tiny fraction of rail rapid transit fatalities—probably not more than one death in the approximately 2 billion people carried each year, During the 5-year period studied for CTA and PATCO and during the 3 years of BART operation, there have been no passenger deaths on trains or station platforms as a result of transit operations. In NYCTA between July 1969 and October 1973, there were five deaths related to train operation (three caught in doors and two killed in a collision).

Examination of the accident records for newer transit systems reveals that the patrons' experience with rail rapid transit seems to be more of a contributing factor than the difference between manual and automated modes of operation. Accident rates in the first year of operation of a new transit system to be three or four times higher than for older and established systems or for the same system after the public has gained riding experience. Figure 49 shows the history of train motion accidents for the PATCO Lindenwold Line and the Dan Ryan extension of the CTA West-South Line, both opened for service in 1969. Comparable data for the first 3 years of BART operation are also shown. PATCO and BART have automated train operation. Trains are operated manually with cab signals on the Dan Ryan Line. For comparison, the train motion accident rates for CTA as a whole are shown for the 5-year period 1969–73. Here, the rate for a presuma-

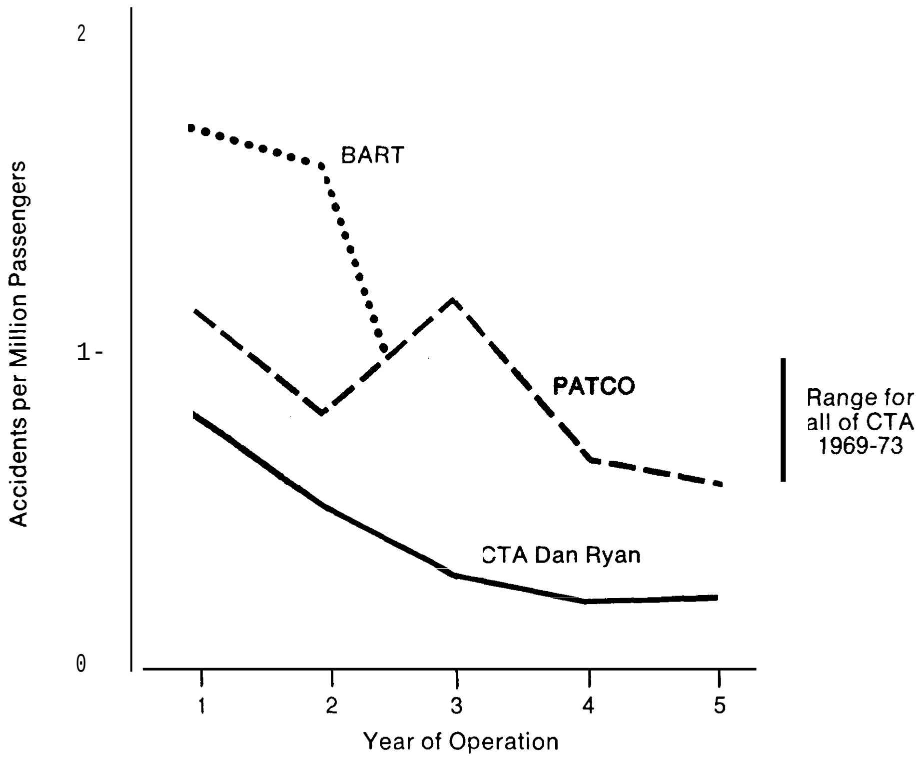

FIGURE 49.—History of Train Motion Accidents

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bly experienced riding public is steady between 0.6 and 1.0 per million passengers, a range which includes the latest figures for PATCO and BART.

A similar learning phenomenon appears in the pattern of door closure accident rates. The rate in BART for the first year (1972–73) was 5.5 per million, but it declined to 4.3 and then 1.6 in the next year and a half. In PATCO, the decline was from 2.7 to 1.4 over a 4-year period (1970–73). In CTA as a whole, it fluctuated in the narrow range of 1.0 to 1.4. Since car door operation is automatic in BART and manual in PATCO and CTA, automation does not appear to have anything to do with the accident rate. All three systems seem to be approaching, or to have reached, a common floor of about 1.0 to 1,5 per million passengers.

ISSUE O-3: DESIGN SAFETY

With respect to design and engineering, are ATC systems safe?

On theoretical grounds, ATC is at least as safe as manual control, and probably safer. However, there is insufficient evidence from actual transit operations (except in the area of ATP) to evaluate safety empirically. There is also some difference of opinion in the transit industry on how to assure the safety of a design.

The rail rapid transit industry is extremely conscious of safety, which is customarily defined as "freedom from fatalities or injuries resulting from system operation. " Safety-consciousness is reflected not only in the approach to transit operations but also in the design and engineering of track, wayside equipment, and rolling stock. All components judged to be critical to safety ("vital" components, in transit engineering parlance) are designed according to the fail-safe principle. Stated simply, fail-safe is "a characteristic of a system which ensures that any malfunction affecting safety will cause the system to revert to a state that is generally known to be safe"[47] (NTSB, 1973).

The fail-safe principle appears to be applied as rigorously to the design of ATC as to other transit system components, and probably even more so because of the concern engendered by removing the human operator from direct involvement in train control functions. Therefore, at the design level at least, there is no reason to conclude that automated train control systems are not as safe as manual systems. They may even be safer because possible hazards due to human error and variability have been eliminated by substitution of machine components.

But has this substitution merely replaced one form of hazard with another, perhaps to the general detriment of system safety? This question goes to the heart of the automation issue, but it is largely unanswerable at present for two reasons. First, there is very little empirical evidence from automated systems by which to judge safety historically, except for the case of ATP.[48] Second, there are no generally acceptable criteria by which to evaluate safety from a theoretical viewpoint, especially when comparing dissimilar systems.

At present, there are only two operational rail rapid transit systems in the United States with a substantial degree of automation for functions other than ATP. PATCO, opened in 1969, has ATP and ATO, However, PATCO is a system consisting of only one line, and therefore neither representative of a large urban mass transit system nor a true test of automation technology. On the other hand, the safety features of PATCO are impressive, reflecting both safety-consciousness in design and awareness of the realities of rapid transit operation. The safety record attained by PATCO is excellent and attests to the basic safety of ATO, at least at that level of automation and in a system of that complexity.

The San Francisco BART system is more highly automated than PATCO, incorporating ATS as well as ATP and ATO, but the system is relatively new and still undergoing start-up problems. Testing and evaluation prior to full operational certification are still being conducted by the California Public Utilities Commission, However, even before

[47] The exact interpretation of the fail-safe principle is difficult under some conditions, especially where it may lead to stoppage of a train in hazardous circumstances, e.g., a tunnel fire. A discussion of this point is presented later, beginning on page 86.

[48] The traditional view of transit engineers is that the safety of a transit system is wholly assured by train protection functions and that ATO and ATS play no part in safety. This is correct if safety is defined simply as the prevention of collisions and derailments. However, if safety is defined more broadly as the freedom from injuries or fatalities resulting from system operation (the view taken here), then the safety of ATO and ATS equipment becomes highly germane.

*

revenue operations began in late 1972, BART was the subject of intense public controversy over the safety of ATC design, and the debate continues even now. The concern over ATC in the transit industry and in State and Federal Government bodies seems to have been engendered by the BART experience. Nevertheless, it appears that the difficulties besetting BART result more from specific engineering defects and management problems than from any inherent shortcoming of ATC technology itself.

The application of automation technology in rail rapid transit is not, of course, limited to PATCO and BART. There are individual lines within larger systems (e.g., the CTA Dan Ryan extension and the Quincy extension of the MBTA Red Line), but the extent of automation is not so great as in PATCO and BART, consisting only of ATP and machine-aided train operation by means of cab signaling. Also, the results in CTA and MBTA are hard to distinguish because of the merger of the cab-signaled portions into lines with other forms of signaling and train control.

Outside of rail rapid transit there are some nine automated guideway transit (AGT) systems[49] in the U. S., such as the Dallas/Fort Worth (AIRTRANS) and the Seattle-Tacoma (SEA-TAC) airport systems, operating without a human controller on board. The adequacy of ATC with respect to design safety has been generally established in these systems, which employ a technology derived from rail rapid transit. However, there is some question whether this experience is transferable back to the parent rail rapid transit technology. Speeds are generally lower in AGT; vehicles are smaller; and the lines are fewer, with less complex interlocking.

Thus, the pool of operational experience with ATC in rail rapid transit is rather small, consisting of 6 years of relevant data from a simple one-line system (PATCO) and 3 years from a complex system (BART), There is also fragmentary evidence from the CTA Dan Ryan and MBTA Red lines, where the level of automation is lower and not characteristic of the system as a whole, The data from AGT may or may not be applicable to rail rapid transit because of certain basic differences of scale and complexity.

FIGURE 50-Unmanned Train at Seattle-Tacoma Airport

The opinion of transit system managers with regard to the safety of ATC is significant. A recent survey of transit system safety problems, conducted under UMTA sponsorship, did not identify ATC as an area of concern. Priority action was recommended for several safety problems; but train control systems and automation were not mentioned, even though these topics were listed in the survey form circulated among transit system operating authorities (Transit Development Corporation, 1975).

[49]Automated Guide way Transit (ACT) is a general designation for transportation systems operating relatively small, unmanned vehicles+ ither singly or in trains-on fixed guideways along an exculsive right-of-way, See the OTA report, Automated Guideway Transit (Report No, OTA–T–8), June 1975, for an assessment of this type of transit technology.

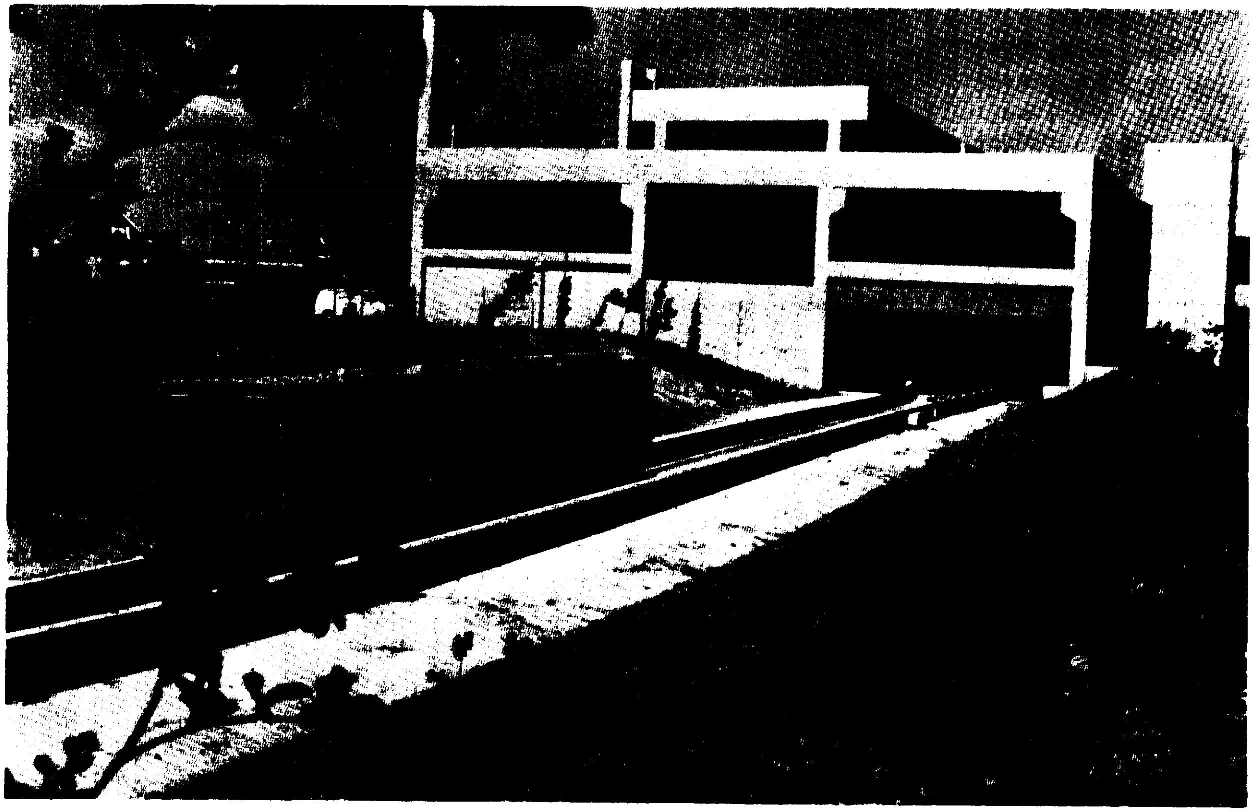

FIGURE 51.—Fully Automated AIRTRANS Train

The matter of available data on operating experience aside, there remain more fundamental questions of methodology and criteria. How is safety to be measured, either empirically and theoretically? How safe is safe enough? What is meant by safety? Is ATC Safety equitable with the train protection function, or are there safety implications in ATO and ATS? Not all these questions have answers generally accepted by experts in the field of safety and train control engineering.

A study of ATC safety conducted by the DOT Transportation System Center (1974) reached the conclusion that it is "literally impossible to achieve fail-safe design in a large complex control system having many interacting elements and functions." No matter how carefully designed and tested a system may be, there will always be certain combinations of component failure or operational conditions that cannot be wholly compensated for. The probability of such events, although infinitesimally small (1×10^{-6} or less), represent potential safety hazards that must be dealt with. In other words, no system as large and complex as a rail rapid transit system can be made perfectly safe. Some risk must always be taken.

And so, on theoretical grounds, the question of ATC safety reduces to a matter of probabilities and acceptable levels of confidence, At the present time, there is some disagreement within the transit industry and among Federal and State regulatory agencies as to how these probabilities are to be estimated or what measure of risk is tolerable.[50]

The traditional design approach followed in the transit industry for ATP has been the fail-safe concept, where the essential concern is the immediate or short-range response to protect the system from the consequences of component or human failure. Customarily, this protection is achieved by initiating a shutdown or reversion to a lower level of performance (e.g., decreased speed, greater headways,

[50]Transit system professionals have also taken issue with the general approach and some of the conclusions of the TSC study.

longer station dwell time). The difficulty with this approach is that most modern transit systems operate on very short headways. Thus, if a failure occurs, it is not simply a matter cf stopping one train. The effect reverberates through the entire system, or a large part of it, requiring that many other trains be stopped or slowed until the failure can be corrected, Such sudden and unexpected changes in the operating mode of the system can produce a risk situation that pervades far beyond the point of failure and persists long after the failure has been corrected. Thus, application of the fail-safe principle may produce a response which is safe for the immediate and local circumstances but which also produces longer-term and more far-reaching consequences for the general safety of the system.[51] (NTSB, **1973)**

As a supplement to the fail-safe approach, NTSB has advanced the concept of total system safety. The first step of this approach is to select system goals, e.g., prevention of collisions and derailments. The system is then analyzed with respect to these goals to determine where the system could fail and allow a collision or derailment to happen. The analysis permits construction of a "fault tree, " which includes not just single component failures, but also multiple failures and environmental interactions, making it possible to identify those parts of the system which are critical to safety and to trace out the paths where failure must be prevented from compromising any of the system safety goals. This, in turn, shows the designer the parts of the system which must be provided with redundant components, functionally equivalent mechanisms, self-checking circuits, or inhibitory devices. Through application of statistical techniques, it is also possible to evaluate the likelihood of failures and adverse circumstances and thereby place the assessment of risks on a quantitative basis. (NTSB, 1973; Battelle, 1975)

The approach suggested by NTSB recognizes that the safety of the system as a whole is not equivalent to the safety of its parts and offers an alternative method to assess interactive and combinatorial effects of component failure. The NTSB approach also offers a way to identify hazards on a system-wide basis and to make explicit the level of risk imposed by each. However, both the methodology and validity of this approach have been challenged by transit system engineers. Some maintain that the fail-safe principle-correctly applied—is adequate and proven by experience and that there is no need for recourse to a total system safety concept, Others contend that the NTSB approach offers nothing new and that it is only a restatement of the safety analysis methodology customarily applied as part of the fail-safe approach.

In summary, the safety of ATC design (except for ATP) has not been conclusively determined. With respect to the theoretical safety of ATC, adequate precautions appear to be taken in the design process to assure that automated devices result in a level of safety at least as high as that conventionally attainable with manual means of train control. The absolute safety of ATC devices cannot be ascertained by any safety methodology, criteria, or design philosophy currently employed in the transit industry. Empirically based judgments about the safety of ATO and ATS can be only tentative at present because data are limited to a few systems for only relatively short periods. With respect to ATP, the available evidence indicates that automatic methods are safer than manual train protection. In practical terms, accidents due to defects of train control (either manual or automatic) are events of very low probability-estimated here to be on the order of one injury per million passengers and one fatality per billion passengers, rates which are among the lowest of all modes of transportation.

ISSUE O-4: PASSENGER SECURITY

Does reduction in the number of on-board personnel, brought about **through** ATC, have an adverse effect on passenger security from crime?

There is no evidence to suggest that passenger security on trains is affected by reducing the size of the train crew.

The security of passengers from criminal acts in stations and on trains is a matter of serious concern to rail rapid transit operating authorities. It has been conjectured that automation, because it tends to reduce the number of transit property employees on trains and in stations, might have an adverse effect on passenger security. Passengers, especially on long trains with a crew of only one, might be more vulnerable to assault, robbery, and other criminal

[51]Some members of the transit industry have disputed these conclusions on the grounds that NTSB has misinterpreted the fail-safe principle and that the concept of pervading risk is appropriate to aviation hot not to a transit system.

acts because the only transit employee who could render assistance is located at the front end of the train, often in an isolated compartment, giving full time and attention to train operation or supervision of ATC equipment.

This line of reasoning has been advancd primarily as an argument against reducing the number of on-board employees as a result of automating train control functions. The argument also bears indirectly on the justification for ATC itself, If personnel in addition to the train operator (the so-called second and third men) are to be kept on board anyway for security purposes, then they could assist in train operation by performing manually such functions as door operation, train announcements, and equipment monitoring.

The managers of operating transit systems tend to the belief that personnel on board the train have a favorable influence on security, both in protecting passengers from robbery and assault and in deterring vandalism to the train itself. Agencies planning new systems generally hold the same view, and those planning to have only one or no on-board attendant intend to compensate by having more station personnel and roving security employees,

The operating transit systems have greatly varying approaches to passenger protection and train policing. NYCTA maintains a very large transit police force (5,100, the eighth largest police force in the country), with patrolmen posted in stations and on the trains themselves during certain hours and in high crime areas. PATCO has a rather small transit police force (20 men), which includes a dog unit that patrols the property during the rush and base periods and rides the train during owl service. BART also has its own police force; but considering the size of the property, the force is small (99 members, of which 63 are in patrolling platoons). In contrast, CTA has no transit police force as such; passenger security protection is provided by the police departments of the municipalities served.

There is, however, no firm statistical evidence to support the contention that presence of operating personnel or police on the train does, in fact, promote passenger security, Crime statistics for four transit systems (BART, CTA, PATCO, and NYCTA) are presented in table 13. Data for other systems are not available, but anecdotal information suggests that the rates are roughly comparable to those shown.

Caution should be observed in interpreting these data. The four transit systems shown here differ greatly in such characteristics as hours of operation, security measures, and types of communities served. There are also slightly differing definitions among the four as to what constitutes robbery or assault. For example, some include purse snatching in the category of robbery, while others do not. Some list sex offenses separately; some combine such crimes with other forms of assault. An attempt has been made to reduce the statistics presented here to a common base, but some distortions undoubtedly remain. Therefore, the rates given in table 13 should be taken only as an indication of the rough dimension of the problem and should not be considered to show the relative degree of passenger security in the four systems.

TABLE 13.—Passenger Assaults and Robberies for Selected Transit Systems

SYSTEM	ASSAULT/ROBBERY RATE (per million passengers)
BART (1973–74)	2.96
CTA (1969–73)	1.44
NYCTA (1973/74)”	3.49
PATCO (1969–73)	0.24

● July 1973 to June 1974.

While only limited conclusions can be drawn from this sample of data, there does not seem to be any clear relationship between crime rates and the number of operating personnel on the trains, For example, PATCO with only one operator on the train and unmanned stations has a rate that is an order of magnitude lower than NYCTA, where there are two men on board and police actively patrol trains and stations. Also, the rates in BART and NYCTA do not appear to differ substantially even though the two systems are vastly different in terms of automation and the level of train and station manning.

The dominant factors influencing security seem to be the size of the city and the sociological characteristics of the areas served. It should also be observed that, if ATC has any influence at all, it is likely to be small since the preponderance of crime in rapid transit systems (75–80 percent) does not

FIGURE 52.—Approach to Brightly Lighted Station

take place on trains, but in and near stations. A study conducted by the American Transit Association (1973) concluded that station security was by far the more critical problem and that station crime was concentrated in neighborhoods of generally high crime, usually near the residence of the criminals, Anecdotal evidence from transit properties interviewed also indicates that the areas of greatest concern are stations, access ways, and parking lots and that patrols are concentrated there. In light of this, it is perhaps significant that most transit-properties list all assault and robbery statistics under the general heading of station incidents.

As a final comment, a distinction must be made between the real (i.e., statistically measurable) security of passengers and their perception of security while using a transit system, In the area of

FIGURE 53,—Lonely Station at Off-Peak Hour perceived security, most transit operators and planning agencies agree that the on-board employee plays a useful and reassuring role. Communications of any and all forms are also believed to be useful for enhancing perceived (and real) security of patrons. Two-way communication with passengers is regarded as mandatory for systems with unattended vehicles. Surveillance of train interiors by closed-circuit television is technically feasible, but most properties consider the cost of purchasing and operating the equipment to be prohibitive in comparison to the potential benefits.

Data on the perceptions of passengers themselves do not exist in any meaningful quantity. In one of the few studies made of passenger attitudes, a telephone survey of 1,586 bus and rail rapid transit patrons in Chicago, it was found that passengers would derive the greatest sense of security from the presence of a police officer on the train or platform and from the knowledge that help was available quickly from station personnel or the police. Few respondents (8 percent) mentioned the presence of a conductor or motorman as a reassuring factor. This survey also found that CTA patrons tended to regard subway stations and elevated platforms as more dangerous than the trains themselves. (ATA, 1973)

PERFORMANCE

The operational characteristics of ATC can affect the general performance of a transit system in several ways. Some may be qualititative; others quantitative. Some may directly affect transit patrons and be perceived by them as benefits. Other performance characteristics may be of concern primarily to the operating authority and go largely unnoticed by the riding public. Those selected for examination here are the more tangible and measurable aspects of system performance, where differences between manual and automated forms of train control might be manifested as benefits for either the transit patron or the operating authority. They are:

Ride Quality—the smoothness and comfort of the ride, expressed in terms of speed and its derivatives (acceleration and jerk);

Level of Service—the convenience and dependability of the transit system, measured as headway, trip time, available seating, and adherence to schedule;

Availability—the ability of the system to sustain the required level of daily service, as indicated by the reliability and maintainability of equipment.

As in the preceding discussion of safety, the performance of ATC systems is treated as a series of issues, with operational experience from various cities presented in tabular format to substantiate the conclusions. This method of presentation tends to invite comparisons among transit systems; and it is intended that the reader do so, but only within the limits set forth in the discussion of the issue. Some differences are more apparent than real, They arise either from different definitions and recordkeeping methods or from differences among systems that have nothing to do with train control (e.g., track geometry, right-of-way conditions, station spacing, environmental factors, age of equipment, and so on). An effort has been made to reduce all data to a common base and to use standardized terms, but there still remains a need for caution in making direct comparisons across systems.

ISSUE O-5: RIDE QUALITY

What effects does automatic train operation (ATO) have on ride quality and comfort?

ATO systems provide a ride quality equal to that of manual modes of operation. Some consider ATO systems superior in that the ride quality is more uniform.

Ride quality is a general term referring to the smoothness and comfort of train motion as perceived by the passenger. It is measured in terms of the acceleration and deceleration characteristics of the vehicle while running at speed and during arrival and departure from stations. Ride quality is influenced by many factors—propulsion and braking system characteristics, vehicle suspension, track geometry, condition of the right-of-way, wheel-rail adhesion, signal system design, and speed regulation technique. Of these, only the last two fall within the province of the train control system, and they usually do not have a major influence on ride quality. Vehicle and track characteristics are by far the dominant factors. However, the train control system can play a part in enhancing ride quality or in compensating for adverse effects produced by other factors.

In terms of train control functions, ride quality is governed by those elements of the system that regulate speed and execute programed station stops. Three aspects of motion must be controlled: speed, acceleration, and the rate of change of acceleration.

Acceleration and deceleration (the rate at which speed changes) is related to, but not actually a part of, the speed regulation function of the train control system.[52] For passenger comfort, as well as safety, the changes in velocity must be kept within certain limits when running the train up to speed and when coming to a stop at stations. Different rates may be employed-a nominal rate for service braking and a somewhat higher rate for emergency stops.

It is important to control not only acceleration but also jerk—the rate of change of acceleration, so named because of the uncomfortable (and potentially hazardous) effect produced by abrupt changes in acceleration or speed.[53] Control of jerk, more than control of acceleration itself, contributes to a smooth ride and, for the standing passenger, a somewhat safer one. Jerk limiting applied during stopping is sometimes called flare-out control. It is identical to the technique employed by a skilled automobile driver when coming to a stop. By easing off on the brake, the transition from deceleration to full stop is smoothed or feathered out. Because there are safety implications to relaxing braking effort while stopping, flare-out control (a train operation function) is overridden by the train protection (ATP) system such that flare-out is prevented during emergency braking.

Maintaining optimum wheel-rail adhesion is called slip-slide control. Slip denotes the slipping or spinning of wheels during the application of power. Slide denotes the sliding or skidding of wheels when brakes are applied. Both are operationally undesirable because they represent inefficiency in running the train and may cause damage to tracks, wheels, or the propulsion and braking system of the train. For the passenger's perception of ride quality, slip-slide control is only marginally important, but it does affect jerk characteristics. There are also safety implications; the system is usually designed so that failure of slip-slide control does not allow release of brakes when safety requires that they be applied.

In transit systems where trains are operated manually, speed regulation, slip-slide control, and flare-out are usually performed by the motorman.[54] The ride quality resulting for the passenger is thus determined by the skill or artistry of the individual motorman and the consistency with which he applies proper technique. In transit systems with ATO, these three functions are usually automatic. The use of automatic mechanisms is generally considered to offer two advantages. First, the train is more likely to be operated within the limits acceptable for passengers and equipment because the control system is designed to preclude human error and improper technique. Second, automatic operation leads to less variation; human control varies considerably with individuals and time.

Table 14 is a summary of the speed regulation, jerk limiting, and slip-slide control methods employed in five operating transit systems. The new transit systems planned for Washington, Atlanta, and Baltimore will all employ automatic techniques similar to those of PATCO or BART.

There is almost no empirical evidence to support or refute the advantages claimed for ATO on theoretical grounds. Systematic studies in experimental settings or under actual operating conditions have not been conducted, and there is no effort now under way to do so. The opinion of some transit system engineers is that ATO leads to a ride quality and type of train operation that is at least as good as manual control, and perhaps even superior because of the ability of automatic devices to operate within prescribed tolerances more consistently. Transit system managers also seem inclined to this view. There is, however, some dissenting opinion from both engineers and managers. Perhaps the most conclusive indication that ATO is preferable to manual control is that all the transit systems now under development and most of the proposed extensions or improvements to existing systems will

[52] Acceleration and deceleration control is considered by transit engineers to be a part of the traction system. While it is true that the equipment controlling acceleration and deceleration is physically a part of the traction system, the functional boundary between this system and the train control system is somewhat fuzzy, and a case can be made for treating acceleration and deceleration control as part of either one, In practical terms, the (Distinction is [unimportant since speed regulation, acceleration and deceleration control. and jerk limiting all interact to produce a smooth ride.

[53] Jerk limiting is also considered technically a function of the traction system. The train control system commands a specific level of acceleration. and the propulsion system responds by application of power or braking to produce acceleration/deceleration at a rate within allowable equipment or human tolerances,

[54] Jerk limiting is automatic on all operating transit systems and is built into the propulsion system.

FIGURE 54.—Comfort Features of Modern Transit Cars

TABLE 14.—Train Operation Methods Related to Ride Quality

TRANSIT SYSTEM	ACCELERATION	ACCELERATION RATE JERK LIMITING	 FLARE-OUT	SLIP-SLIDE
NYCTA	Automatic[1]	Automatic	Manual, except on new R–44 and R-46 cars when operating with ATO	Manual, except on new R–44 and R–46 cars
CTA	Automatic[1]	Automatic	Manual	Manual
MBTA	Automatic	Automatic	Manual	Manual, except on new Red Line cars
PATCO	Automatic	Automatic	Automatic on service brakes, except in manua1 backup mode: none on emergency brakes	Automatic in all propulsion and braking modes, including emergency braking
BART	Automatic	Automatic	Automatic on service brakes, except in manuall back-up mode: none on emergency brakes	Automatic in all propulsion and braking modes, including emergency braking

[1]Inherent in propulsion system design.

incorporate automatic control of acceleration, jerk, flare-out, and slip-slide.

ISSUE O-6: LEVEL OF SERVICE

Do transit systems with ATC provide a level of service that is comparable to manually controlled systems?

Generally yes, although some systems with ATC have encountered difficulty in maintaining schedules, especially during the initial months of service.

Level of service is a general term that includes both the characteristics of the service offered (speed, trip time, frequency of trains) and the debendability of that service. Designers of transit systems consider these aspects of service, along with comfort and convenience, to be determining factors in gaining and holding public patronage. The assumption is that if travel time can be saved by using rail rapid transit, if service is available when wanted, and if there is assurance that the trip will be completed according to schedule, a large share of the public will choose rail rapid transit over other modes of transportation, Advocates of automation contend that ATC offers the means to upgrade service by making it possible to operate trains at greater speeds, on shorter headways, in closer conformance to schedule, and with greater regularity,

Maintaining a high level of service depends on how well both the train operation and train supervision functions are carried out. The elements of the system responsible for operating trains, whether the motorman or an automatic device, must assure that trains are run at the prescribed speeds, making the scheduled stops and departing from stations after the specified dwell times. The train supervision function, either by humans or computers, entails monitoring the performance of individual trains in relation to overall passenger demand and making compensating adjustments of schedule, running time, station stops, and dwell time as necessary to overcome irregularities of train operation, variations in demand, or adversities of weather. The success of this combined train operation and supervision activity is measured by schedule adherence, i.e., the percentage of time that trains are actually run according to schedule, making the prescribed stops, and with the requisite number of cars.[55]

Table 15 is a summary of the service-related performance characteristics of five transit systems with various degrees of automation of train operation and supervision functions. Also shown are the service characteristics of the AIRTRANS system at Dallas-Fort Worth Airport. Although AIRTRANS is an airport people-mover system in the AGT class and not a true rail rapid transit system, it has been included as example of a wholly automated system operating without on-board personnel. No existing rail rapid transit system operates in this manner. The data for AIRTRANS, BART, PATCO, and NYCTA apply to the entire system. The CTA and MBTA data are for only the most automated lines.

The speeds and headways for the two rail rapid transit systems with ATO (BART and PATCO) are generally equivalent or superior to those of the systems with manual train operation.[56] It must be noted, however, that maximum speed is little influenced by ATO. Speed is mainly a function of track condition, vehicle characteristics, age of equipment, and station spacing, to name a few. Thus, the higher speeds attained in BART and PATCO do not necessarily reflect an y superiority of ATO over manual operation. These systems are newer, in better condition, and built for different purposes.[57] The track and rolling stock have been designed for high-speed operation. Station spacing permits longer runs at maximum speed, thereby raising the average line speed, Still, the data do suggest that systems with ATO are capable of providing a level of service at least equivalent to that of manual systems,

With regard to headways, ATO does seem to offer advantages over a manual system. Headway is basically determined by the level and qua lit y of signal protection (ATP) and the regularity with which

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[55] Ultimately, level of service depends more on management policy than technological features, since it is management that sets the desired level of service and determines the degree of commitment to maintaining service in the face of adverse circumstances,

[56] Speed in the AIRTRANS system is substantially lower, but this is a result of very close station spacing (typically 1,000–2,000 feet) which does not permit vehicles to operate at maximum speed for more than a few seconds.

[57] BART and PATCO are basically interurban systems more comparable to the Long Island Rail Road or Penn Central's commuter services than to the NYCTA or CTA urban transit systems.

TABLE 15.-Service Characteristics in Typical Transit Systems

TRANSIT SYSTEM	AUTOMATION			SPEED (mph)		HEADWAY (min.)		Maximum Train Length (cars)	Trips/Day (each way)	One-Way Trip Time in Peak Period (min.)
	ATP	ATO	ATS[2]	Max,	Av.	Peak	Base			
NYCTA	J			50	20	2	10–12	11	8,000	359
CTA (Dan Ryan)	~			55	30	3	5	8	225	42 1/2
MBTA (Red Line)	4	J[4]		50	30	2 1/2	4 1/2	4	255	25
PATCO	l l	J		75	40	2	10	6	182	22 1/2
BART	J	J	J	80	40	56	6	10	[5]280	54–57
AIRTRANS	J	d	d	17	9	[6]1	–	2	–6	–6

[1]A check (√) indicates the function is automated. All but AIRTRANS have an on-board operator to run the train or monitor automatic system performance.

[2]Automation here specifically means computer-aided central control.

[3]System-wide average; trip time on individual lines varies considerably as a function of line length and whether service is local or express.

4A portion of the route is equipped for ATO but currently operates under manual control, Cars are capable of 70 mph top speed but are governed to so mph for manual operation.

[5]The figures are for interim level of service; when fully operational, approximately 600 trips per day will be run at headways of 2 minutes during peak periods and 4 minutes during the base period.

[6]AIRTRANS operates 17 overlapping loop routes of varying length. Trains circulate continually throughout the day on a schedule determined by aircraft arrivals and departures.

trains are operated, i.e., the invariance of running time. There is a large, but not unanimous, body of opinion among transit engineers and managers that ATO is necessary in order to operate trains at high speeds on short headways. Given a signal and train protection system of good quality, trains can be run manually on short headways, viz., NYCTA or CTA, where scheduled headways on individual lines are on the order of 1–2 minutes and composite headways on merged lines sharing a single track may be 40–50 seconds. Given the proper equipment and track conditions, trains can also be run at high speed under manual control. Metroliners have operated manually in regular service at speeds of up to 130 mph. But some transit engineers and planners believe that the combination of high speed and short headway cannot be attained without the help of ATO to eliminate the variability of manual operation.

Data to support this contention are scarce because there is only one transit system (PATCO) where manual and automatic modes of operation can be directly compared. The PATCO trains are normally run under ATO, but full-speed manual operation is possible as an alternate mode and is, in fact, required of each train operator once a day as a means of maintaining proficiency. The PATCO experience has been that the trips run under manual control average about 20 seconds longer and are of much greater variability than ATO runs, Since these manual proficiency trips are not run during peak periods, the impact of longer and more variable running time on headway is hard to assess, but the effect might be to increase headway and so lessen the overall throughput of the system. On the other hand, the PATCO results may be misleading because they were obtained while running with a clear track ahead. Some transit engineers contend that, when trains must follow closely or when track and weather conditions are adverse, the manual operator is superior to the automatic device; and trains can be run more uniformly, at closer headways, and with shorter running times,

For the transit patron, the schedule of train service is only part of the equation. The patron also requires assurance that the schedule will be maintained with a high degree of consistency. That is, the performance history of the system must lead the patron to the conclusion that he can rely on the trip being completed, on time, without skipping scheduled stops, and with the customary amount of car space available.

FIGURE 55.—The Wait .... and the Rush to Leave

Schedule adherence of transit systems is not strictly comparable because of differing definitions of on-time performance and dissimilar methods of keeping operational logs. For example, some systems consider a train on time if it arrives at a terminal within the turnaround time, i.e., in time to depart on schedule for the next run. Others use an arbitrary definition, such as a delay not exceeding 5 minutes, either at a terminal or at checkpoints along the route. Still others, such as BART, use a more dynamic and detailed measure of schedule adherence that takes into account the impact of individual delays on total system performance.

Schedule adherence is also influenced by the strategy employed in setting a schedule. One approach is to base the schedule on maximum train performance (maximum attainable speed, acceleration, and deceleration and minimum coasting time) with the expectation that maximum throughput will be" achieved except for a small fraction of the time when complications arise. An alternative approach is to schedule trains at something less than their maximum performance, thereby creating a built-in reserve of performance that can be used to make up delays en route. This approach sacrifices some throughput but offers greater assurance that the schedule can be met.

Because of these dissimilarities in setting schedules and defining on-time performance, direct comparisons across transit systems cannot be made, The following data, therefore, should be regarded only as individual examples of schedule adherence for representative transit systems.

PATCO

A train is considered late in PATCO if it arrives at a terminal more than 5 minutes behind schedule. PATCO keeps a daily log of lateness and other schedule anomalies such as trips annulled, station stops missed, and trips made with less than the scheduled number of cars (short consist). Table 16 shows the performance figures for 1974 and for an average year in the period 1970– 74.

PATCO also computes an overall index of schedule adherence:

$$\text{Schedule Adherence} = 100\,\frac{T_s - T_a - T_l - 0.1\,(Sb)}{T_s}$$

where:

T_s = trips scheduled

T_a = trips annulled

T_l = trips late

Sb = stations bypassed

Applying this formula gives a figure of 98.71 percent schedule adherence in the 5-year period 1970–74 and a figure of 98.34 percent in 1974. It is worth noting that in 1974, despite a derailment due to traction motor failure and a subsequent schedule disruption caused by replacement of motor bearings for all cars in the fleet, PATCO was able to sustain a level of performance nearly equal to that of the preceding 4 years—98.34 percent in 1974 versus 98.80 percent in 1970–73.

TABLE 16.-Schedule Adherence in PATCO, 1970–74

PERFORMANCE	1974	FIVE-YEAR AVERAGE (1970-74)
SCHEDULED TRIPS		
Percent on time	98.36	98.75
Percent late	1.16	1.03
Percent annulled	0.48	0.23
SCHEDULED STOPS BYPASSED (%)	0,18	0.40
TRIPS MADE WITH SCHEDULED NUMBER OF CARS (%)	99.66	99.75

CTA

CTA has a very stringent definition of lateness and employs a complex strategy to compensate for delays, A train is considered late if it is more than 30 seconds behind schedule at a terminal or intermediate checkpoint, When this occurs, preceding and following trains are deliberately delayed also so as to minimize irregularity in headways and balance the service.

For the purpose of this report, a special study was made of schedule adherence on one CTA line, the West-South (Lake-Dan Ryan), which is one of the newest lines and operates with cab signals. On-time was defined to be arrival at a terminal with a delay not exceeding the scheduled turnaround time, i.e., the actual time of arrival was not later than the next scheduled departure of the train. Depending on the time of day, turnaround time on this line is between 5 and 7 minutes-a standard roughly comparable to that of PATCO. In addition to delay, the analysis also considered the number of trips annulled, scheduled station stops bypassed, and consist shortages, Table 17 is a summary of findings for the year 1974 and for the 5-year period 1970–74.

TABLE 17.-Schedule Adherence on CTA Dan Ryan Line, 1970–74

PERFORMANCE	1974	Five-Year Average (1970-74)
SCHEDULED TRIPS		
Percent on time	96,26	97.37
Percent late	3.65	2.50
Percent annulled	0.09	0.13
SCHEDULED STOPS BYPASSED (%)	0.34	0.26
TRIPS MADE WITH SCHEDULED NUMBER OF CARS (%)	99.93	99.89

Despite certain basic differences between PATCO and the CTA Dan Ryan line in route complexity, track geometry, and station spacing, the performance histories of the two systems are roughly comparable when logged on essentially the same basis. The on-time records of both are on the order of 97-78 percent, and the percentage of stops made and the percentage of trips run with a full consist are nearly 100 percent. Thus, it would appear that a manual system with ATP (CTA) and an automated system with ATP and ATO (PATCO) can achieve equal levels of schedule adherence.

NYCTA

The rapid transit system operated by NYCTA is the largest and most complex in the United States. Automation is minimal, consisting of automatic train protection by wayside signals with trip stops and some automated dispatching. Train operation is wholly manual.

In 1974, the on-time performance record of NYCTA was 97.03 percent, where a train is considered on time if it arrives at a terminal within 10 minutes of the schedule. During 1974, there were 32,515 delays of unspecified length, or about 90 per day or three per line,

AIRTRANS

AIRTRANS at the Dallas/Fort Worth Airport has a fully automatic train control system. Automated trains operate on 17 intermeshed routes over about 13 miles of one-way track. The system is still in the process of shakedown and debugging, having opened for operation in January 1974.[58]

Figure 56 is a plot of the availability of the system on a weekly basis from May to October 1974, where availability is expressed as the ratio of actual hours of operation to scheduled hours of operation. The figure also shows the number of service interruptions experienced each week.

It can be seen that, during the month of May, a relatively few service interruptions caused long delays. In June, the schedule of operation was increased from 105 to 168 hours per week, and the number of service interruptions increased sharply to over 160 per week, or about one per hour. As experience was gained and debugging of the system continued, the length of delay per interruption decreased. By October, system availability averaged over 99 percent, while the number of service interruptions declined to about 40 per week. While serv-

[58] In November 1975 the system was shut down as a result of a contract dispute between the airport management and the manufacturer.

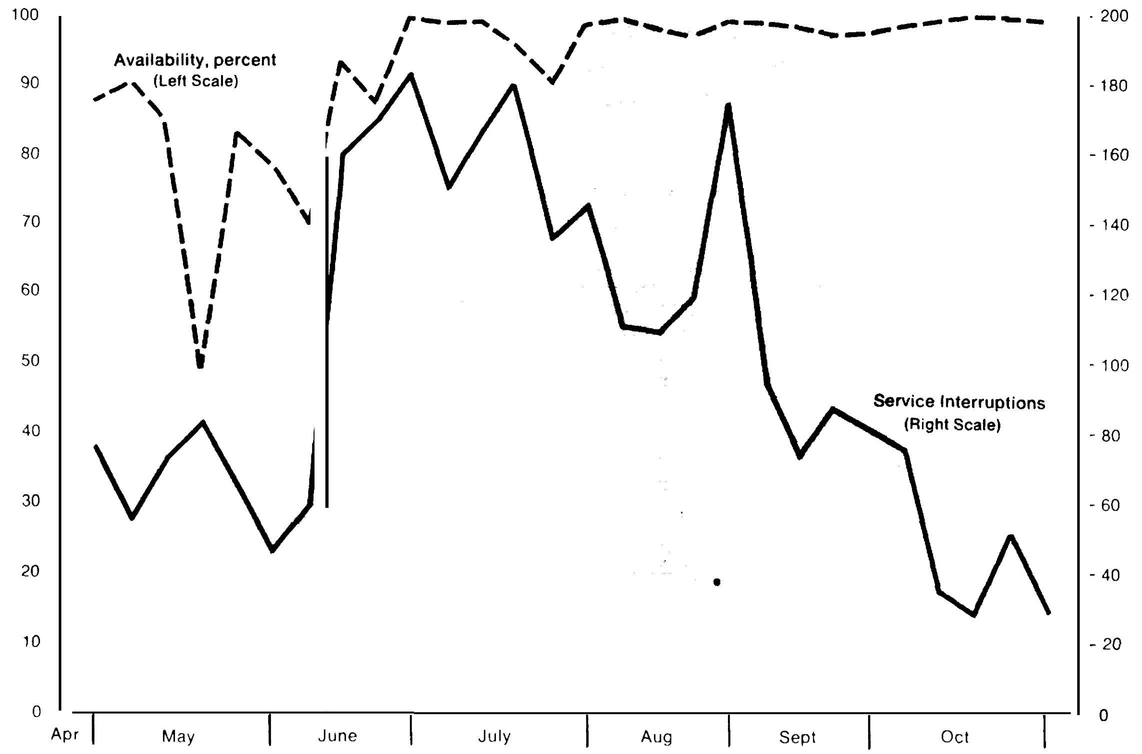

FIGURE 56.—AIRTRANS Availability and Service Interruptions

ice interruptions are not truly equivalent to late trips, it may provide perspective to consider that PATCO experienced about 20 late trips per week and the CTA Dan Ryan line about 54 per week during the first year of operation.

BART

BART has ATO and employs a computer-based ATS system for maintaining trains on schedule, The basic performance index is "total system offset, " an expression of the aggregate delay for all trains operating in the system after application of corrective scheduling algorithms. This measure is more complex than that used by other transit systems, not only because it incorporates more factors, but also because it considers the compensating adjustments which have been applied to following and leading trains, in addition to the late train itself, Thus, a train that is 30 seconds late will result in delays of 5 to 15 seconds for as many as three following and two leading trains, producing a total system offset of as much as 65 seconds while the central control computer respaces the trains and smooths out the traffic flow.

During the first 9 months of operation, under a partial schedule with lo-minute headways, BART experienced severe service disruptions. In the week of 25–29 June, 1973, for example, total system offset averaged about 12 minutes in the morning and increased to over 45 minutes by the evening rush hour. Delays of over 10 minutes were experienced five times during the week, and short consists were run 16 times for periods ranging from 16 minutes to 3 hours.

Table 18 shows a larger sample of data, consisting of weekly performance summaries selected at approximately 4-week intervals from August 1973 to August 1974. During this period, which covers roughly the second year of operation, transbay service had not yet been inaugurated, and BART was running what amounted to two separate systems: Fremont/Richmond/Concord service in the East Bay and San Francisco/Daly City service in the West Bay. Service was limited to the hours of 6 a.m. to 8 p.m., weekdays only.

Examination of the data for the period indicates a slight improving trend with respect to delays, car shortages, and total system offset. The opening of the Transbay Tube in September 1974 caused a sharp decline in the regularity of service for a few weeks; but by the last week of 1974, total system offset was running at an average of 3.6 minutes in the morning and 20.4 minutes in the evening. These figures are roughly comparable to those of August 1974, the month preceding inauguration of transbay service, Still, it appears that the BART system has not yet attained a level of service dependability comparable to other rail rapid transit systems.

Other Transportation Modes

To assess the general quality of service provided by rail rapid transit, it is useful to make some rough

TABLE 18.—Schedule Adherence in BART, August 1973–August 1974

WEEK	WEEKLY TOTAL: Trains Dispatched	WEEKLY TOTAL: Delays Over 10 min.	WEEKLY TOTAL: Short Consist	TOTAL SYSTEM OFFSET (minutes) Daily Average: 7:00 a.m.	TOTAL SYSTEM OFFSET (minutes) Daily Average: 4:30 p.m.
20–24 Aug. 73	116	8	11	8.2	36.0
17–21 Sep. 73	124	10	12	4.8	23.0
15–19 Oct. 73	135	18	21	9.2	45.4
12–16 Nov. 73[1]	149	10	17	9.0	39.8
IO– 14 Dec. 73	166	9	26	9.6	19.0
7 –II Jan, 74	166	9	38	11.8	28.6
18–22 Feb. 74	170	5	17	10.8	22.6
18–22 Mar. 74	172	5	19	3.4	36.6
8–12 Apr. 74	170	8	23	7.8	24.6
13–17 May 74	145	6	25	2.8	16.8
10–14 Jun. 74	162	5	28	2.2	23.6
8–12 Jul. 74	164	2	18	6.6	21.6
5–9 Aug. 74	185	8	26	0.8	15.6
AVERAGE	156	8	22	6.7	27.2

[1]West Bay service began on November 5 1973

comparisons with other modes of public transportation. The on-time performance records of the rail rapid transit systems examined here range from 97 percent for an essentially manual system (NYCTA) to almost 99 percent for a system with ATP and ATO (PATCO). The on-time performance of more highly automated systems such as BART and AIRTRANS cannot be determined from the data available, but it appears to be not lower than 90 percent.

The Metroliner operating between New York and Washington is comparable to rail rapid transit since it operates on a fixed guideway in an exclusive right-of-way and employs similar train control technology, The on-time record of the Metroliner is currently running at about 53 percent, where a train is counted late if it arrives more than 15 minutes behind schedule on a trip of 3 hours. On-time performance for railroads in general exceeds 90 percent for many lines and in some cases reaches 95 percent (Reistrup, 1975).

Air carrier service is a more remote comparison, but still generally valid if limited to flights of about the same duration as a typical rail rapid transit run. The on-time performance record in September 1974 is given below for air carrier service between three pairs of cities about one flight-hour apart:

New York–Washington	79 percent
Los Angeles–San Francisco	84 percent
Los Angeles–Las Vegas	84 percent

(Air Transport World, 1975)

A flight is considered on time if it arrives within 15 minutes of schedule, a less stringent standard than the 5–10 minutes used in the rail rapid transit systems cited above,

ISSUE O-7: RELIABILITY

What effect has ATC equipment reliability had on the performance of transit systems?

ATC equipment poses reliability problems, especially during the initial period of system operation. However, in comparison with other components of the transit system, ATC equipment does not cause a disproportionate share of service disruptions. The problems do not seem to stem from automation per se but from the increased complexity of all new transit system equipment,

The general trip dependability, or schedule adherence, of rail rapid transit systems employing manual or automatic train control was examined in the previous issue. It was found that the method of train operation, either manual or automatic, did not have a major influence. The principal cause of schedule irregularity and service disruptions is not how dependably the train is operated, but how serviceable is the transit equipment itself. Thus, schedule adherence ultimately reduces to a question of whether the equipment can render service when needed.

Technically, the ability of equipment to render service when needed is known as availability and embraces two separate concerns:

(1) Reliability—the ability of the equipment to operate as required at any given time,

(z) Maintainability—the ability of the equipment to be restored to operating condition after failure.

The two are closely related, but only the matter of reliability will be examined here. Maintainability is taken up as the next issue. To provide some perspective for these issues, however, a brief description of the general nature of reliability, maintainability, and availability (RMA) is in order,

Reliability, maintainability, and availability are linked in a relationship that can be expressed mathematically as:

$$A = \frac{R}{R + M}$$

where A = the proportion of time the equipment is available for service

R = reliability, expressed as the time that the equipment will operate as required or as the mean time between successive failures (MTBF)

M = maintainability, expressed as the mean time to repair (or restore) to serviceable condition (MTTR)

In effect, the entire expression reduces to a statement of the probability that the equipment will be available in working condition, or that the passenger will find the transit system fully operational at any given time,

72-683 O - 76 - 8

The general standard in transit systems is for the reliability (MTBF) of major assemblies or subsystems to be on the order of 1,000 hours or more. Repair time (MTTR) is typically 1 or 2 hours. Combining the separate MTBF and MTTR for all subsystems yields on expected availability of roughly 98 to 99 percent for the entire system. The issues to be examined here are whether this expectation is, in fact, realized and what part is played by ATC equipment in the overall RMA picture.

Despite the recognition in the transit industry that reliability is perhaps the single most pressing technical problem, this study did not uncover a significant body of operational data on the performance of vehicle and wayside equipment components. Some transit agencies attempt to maintain a systematic data bank of reliability information, with computer analysis and calculation of component reliability rates (MTBF). Others have a less formal system consisting of shop logs, summaries of individual failure reports ("bad orders"), and other such working records. The methods of recording failures differ among transit systems. Some record failures at the component level, others group these failures in higher order assemblies, such as subsystems or replaceable modules. The definition of what constitutes a failure also varies. Some count reports of failure by train operators; others count only failures confirmed by shop personnel and exclude the so-called "false bad order" or intermittent failure. Still others count only those failures that disable a train or cause it to be removed or withheld from operation.

For those that calculate MTBF, some use a time base that includes all the hours the equipment is actually in operation, counting the time in revenue service as well as the time in yards or on storage tracks when the equipment may be energized but the train not running. Others count only revenue service hours. This difference alone can have significant impact on the calculated failure rate. At BART, for example, it is estimated that yard time is about twice the revenue hours.

As a result, a quantitative analysis of reliability could not be performed in such a way to permit detailed comparison of experience with ATC equipment among transit systems. The following summaries of equipment failure and reliability information for individual systems are therefore not to be compared, except at the most general level and only within the limits noted in the discussion.

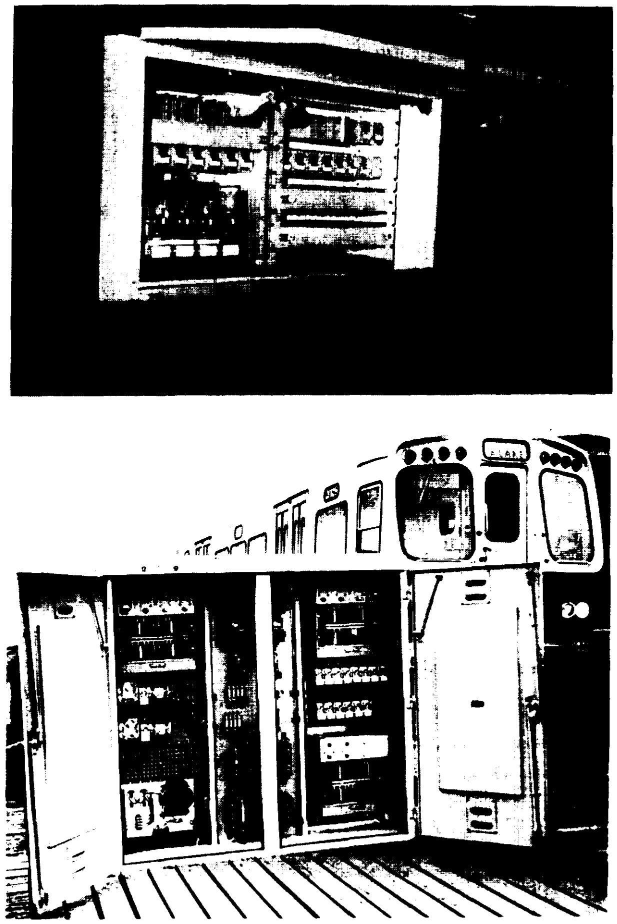

FIGURE 57.--Carborne and Wayside ATC Equipment

PATCO

PATCO has a computer-based reliability and maintenance record system that produces summaries of failure data at 4-week intervals. Table 19 is a sample of car component performance data for a representative 16-week period from mid-July to the end of November 1974. Only certain categories of equipment failure have been selected—ATC equipment and a sample of other major components generally considered reliable. Data on periodic inspection and preventive maintenance have also been included to indicate the proportion of scheduled to unscheduled maintenance events.

It can be seen that ATC equipment failure accounts for about 6 percent of all maintenance events—roughly the same as the propulsion control equipment (cam controller) and air brakes, two conventional items of car equipment that are generally

TABLE 19.—PATCO Car Component Performance, July-October 1974

COMPONENT	NUMBER OF FAILURES						PER-CENTAGE OF ALL FAILURES
	13 JuL-9 Aug.	10 Aug.–6 Sep.	7 Sep.–4 Oct.	5 Oct. -1 Nov.	TOTAL	4-WEEK AVERAGE	
ATC	66	73	100	45	284	71	5.7
. Air Brake	74	52	101	48	275	69	5.5
Cam Controller	47	89	84	68	268	72	5.8
Communication	26	31	30	31	118	30	2.4
Controller	20	17	42	31	110	28	2.2
Coupler	60	72	197	95	424	106	8.5
Master Controller	5	1	7	4	17	4	0.3
Motor-Generator	34	36	56	42	168	42	3.4
All Other	1201	698	788	634	3321	830	66.3
Periodic Maintenance	219	270	449	275	1213	303	

[1]High voltage switches.
[2]Operator's control unit in cab.

regarded as reliable elements. The incidence of coupler failure is about one and one-half times as high as that of ATC equipment. PATCO was experiencing a problem with couplers at that time, necessitating a redesign and replacement of the original equipment. The failure rate for couplers was therefore unrepresentatively high during the sample period. From these data, it can be concluded that ATC equipment at PATCO, accounting for about one failure in eighteen for the all carborne components, is not a reliability problem of disproportionate magnitude.

A separate analysis, performed by Battelle Columbus Laboratory in support of this study, considered only disabling failures[59] and covered a 1-year period from August 1973 to July 1974. These data, presented in table 20, indicate that ATC failures accounted for about 10 percent of all train removals during the year, but with considerable variance. ATC failures, expressed as a percentage of all disabling failures, ranged from as low as 7 percent to as high as 22 percent. Using these data, Battelle also calculated MTBF for vehicles as a whole and for carborne ATC equipment. Vehicle MTBF was found to be 23.9 hours, and the ATC MTBF was about 227 hours, Since cars were operated an average of 30 hours per week, each car had about 1.2 disabling failures per week.

[59]A disabling failure, as defined by PATCO, is one that would require removal of a train or car from service or prevent its return to service after leaving the line at the end of a scheduled run.

ATC accounted for about one-tenth of the removals, or roughly one removal per car every 8 weeks. Thus, ATC reliability accounted for 6 percent of all failures but about 10 percent of removals from service, a reflection of the criticality of ATC to train system performance. Still, the magnitude of disabling failures due to ATC was not large—representing about one incident per car every 8 weeks or, for the whole fleet of 75 cars, 488 removals due to ATC out of the 4,797 experienced in a year,

BART

Like PATCO, BART has a computer-based recordkeeping system for reliability and maintainability information. However, because of differences in the definition of failure and the equipment categories in which data are tabulated, reliability data for the two systems cannot be directly compared. Table 21 is a summary of reported failures by major equipment categories for the period January 1, 1974, to January 21, 1975. Two major classes of equipment are included, carborne equipment and wayside equipment, The latter class includes a substantial amount of train control equipment required for ATP (interlocking control), ATO, and ATS.

The failure of BART carborne ATC equipment accounts for about 11 percent of all carborne equipment failures, a proportion almost identical to that of PATCO, if it is assumed that all the BART

TABLE 20,—Summary of Disabling Equipment Failures in PATCO, August 1973–July 1974

Four-Week Interval Ending	Total Failures[1]	Disabling Failures[2] Number	Disabling Failures[2] Percentage of total	ATC Failures[3] Number	ATC Failures[3] Percent of Disabling
8/10/73	755	425	56.3	73	17.2
9/7/73	1161	777	66.9	47	6.1
10/5/73	1339	913	68.2	95	10.4
11/2 /73	1234	835	76,7	84	10.1
11130/73	1197	769	64.2	78	10.1
12/28/73	1180	788	66.8	56	7.1
1/25/74	1193	716	60.0	57	8.0
2/22/74	1399	839	60.0	69	8.2
3/22/74	1298	807	62.2	53	6.6
4/19/74	962	541	56.2	120	22.2
5/17/74	1105	690	62.4	91	13.2
6/14/74	1197	682	57.0	108	15.8
7/12/74	1206	682	56.6	66	9.7
Total	15,226	9,464	62.2	997	10.5
Average	1,171	728	62.2	76.7	10.5

Battelle calculations, based on PATCO data)

[1]Does not include preventive maintenance or cleaning.

[2]Defined by PATCO to be critical failures that would require removal of a train or would prevent its return to service after leaving the line at the end of its scheduled run.

[3]Does not include communications since PATCO does not consider this disabling.

TABLE 21.-Summary of Equipment Failure in BART, 1974–751

COMPONENT	Number of failures	Average per month	Percent of total failures	Failures per car per month[2]
Carborne Equipment:				
ATC	1,295	102	10.9	0.35
Air Conditioning	504	40	4.3	0.14
Auxiliary Electrical	834	66	7.1	0.22
Car Body	1,676	132	14.2	0.45
Communication	500	40	4.3	0.14
Doors	598	47	5.0	0.16
Friction Brake	1,375	109	11.7	0.37
Propulsion •	4,158	329	35.3	1.15
Suspension	222	18	1.9	0.06
Truck	614	49	5.3	0.17
TOTAL CARBORNE	11,774	932	—	[3]3.16
Wayside ATC Equipment:				
ATO	339	27	21.3	NA[4]
ATP[5]	696	55	43.3	NA
ATS (Central)	41	3	2.4	NA
Power	31	2	1.6	NA
Switch & Lock	198	16	12.6	NA
Yard Control	299	24	18.9	NA
TOTAL WAYSIDE ATC EQUIPMENT	1,604	127	—	—

[1]The period covered is from January 1. 1974 to January 21, 1975, 12.65 months.

[2]Based on an average fleet size of 295 (145 A-cars, 150 B-cars) during the period.

[3]Does not sum because of rounding in individual calculations.

[4]Not applicable.

[5]Includes multiplex and interlocking control equipment.

failures should be counted as disabling. To this, however, must be added the failures of wayside equipment, which in BART accounts for a sizable share of the train control system. BART wayside ATC equipment, including central supervisory (ATS) equipment, experiences about 127 failures per month, the equivalent of 6 per day.[60] In comparison with carborne equipment failures, wayside failures tend to have more widespread consequences because all trains operating in the vicinity (or, if a central control failure, all trains in the system) are affected.

Reliability of equipment has been a major problem in the BART system. For example, an analysis of the operating logs for the period May 1974 to January 1975 shows that only slightly over half of the car fleet was available for service at any given time and that availability declined regularly throughout the day and week. The problem was particularly severe with the A-cars, which contain the train control electronics. In an average week during this period, only 71 of the 148 A-cars (48 percent) were in running condition. From Monday to Friday, availability declined by an average of 8 cars, often leaving fewer than 65 A-cars in service by Friday.

The extent to which ATC equipment reliability contributes to the overall pattern of car problems and service disruptions could not be determined conclusively. The BART staff estimated that ATC was initially cited as the reason for about 20 percent of all train removals, but the actual figure may be somewhat lower if "false bad orders" are discounted and only confirmed ATC failures are considered. Even so, ATC is not the single largest cause of train removal. Propulsion motors, car body defects, and brakes each account for a larger share of car system failures than ATC.

CTA

Automatic train control equipment in CTA consists of wayside signals with trip stops on some parts of the system and cab-signaled ATP on others. Since the extent of train control automation is lower than in PATCO or BART, it would be expected that the proportion of train removals due to ATC failure would also be lower. This hypothesis cannot be conclusively affirmed because CTA does not maintain a formal equipment reliability record that would allow MTBF to be calculated directly. However, a partial analysis, performed as part of this study, sheds some light on the situation.

An analysis of carborne equipment reliability on the West-South route for a representative 16-week period in 1974 was performed by CTA personnel at the request of the OTA staff, The results are shown in table 22. Because two different types of cars are operated on this line (180 2000-series cars and 78 2200-series cars) failures for each are tabulated separately. Cab signal equipment, although listed as a single entry, is of two types-one a rather simple and conventional design and the other more complex and technologically advanced.

Cab signals are the largest failure category for equipment on the West-South route, accounting for 44 percent of the sample of cases reported; but there are several factors operating here that may have distorted the results. First, this is only a partial listing of failures. When considered in the context of all equipment failures, cab signal failures would represent a lower proportion. CTA maintenance personnel estimate that cab signal failures account for no more than 20 percent of all "bad orders." Second, it should be noted that the total of 307 cab signal failures listed in table 22 are reported failures. Shop personnel confirmed only about 60 percent of this number—the remainder being either erroneous reports by motormen or intermittent failures that could not be duplicated in shop tests. This illustrates the general problem of confidence in reliability statistics, where the basic data may be questionable because of incorrect initial diagnosis or the inherent difficulty in troubleshooting electronic equipment. Third, the cab signal failures reported here are not all disabling failures. Some are malfunctions of nonessential features, such as burned-out indicator bulbs, that do not affect the performance of the equipment for basic train protection functions. Fourth, the West-South route was in the process of converting to cab signal operation during the time period considered in this sample, The general experience of CTA has been that equipment reliability is particularly troublesome during the initial installation and check-out period. This is true not only of cab signals but any other new and complex type of transit equipment introduced in an established system.

[60] BART operates only on weekdays, or about 20–21 days per month.

TABLE 22.—Car Component Performance on CTA West-South Route, July–October 1974

COMPONENT	Number of Failures: 13 Jul. – 9 Aug.	10 Aug.– 6 Sept.	7 Sept.– 4 Oct.	5 Oct.– 1 Nov.	TOTAL	4-WEEK AVERAGE	Failures per car per week
Cab Signals							
Reported Defective	(.)	69	73	92	307	77	0.08
(Confirmed)	(.)	(47)	(48)	(51)	(185)	(46)	(0.04)
(Unconfirmed)	(34)	(22)	(25)	(41)	(122)	(31)	(0.03)
Doors							
2000-Series[1]	(13)	(21)	(29)	(29)	(92)	(23)	(0.03)
2200-Series[1]	(26)	(14)	(15)	(16)	(71)	(18)	(0.06)
All cars	39	35	44	45	163	41	0.04
Dynamic Brakes							
2000-Series	(19)	(12)	(19)	(19)	(71)	(18)	(0.03)
2200-Series	(4)	(5)	(5)	(2)	(16)	(4)	(0.01)
All cars	23	17	24	21	87	22	0.02
Friction Brakes							
2000-Series	(7)	(7)	(lo)	(19)	(43)	(11)	(0.02)
2200-Series	(lo)	(14)	(25)	(22)	(71)	(18)	(0.06)
All cars	17	21	35	41	114	29	0.03
Traction Motors							
2000-Series	(3)	(5)	(8)	(4)	(20)	(5)	(0.01)
2200-Series	(3)	(2)	(o)	(o)	(5)	(1)	—
All cars	6	7	8	4	25	6	0.01

[1]Two types of cars are operated: 180 200()-series cars (purchased 1964) and 78 2200-series cars (purchased 1969–70).

NYCTA

NYCTA has wayside signals and trip stops for ATP and virtually no carborne ATC equipment except on the R–44 and R–46 cars.[61] The experience of NYCTA with equipment reliability is, therefore, a useful baseline from which to estimate the general performance of car components other than ATC,

During 1974, there were 32,515 delays in service in NYCTA, about 90 per day. Of these 16,872 (52 percent) were chargeable to car equipment failure. During the same period, wayside signal failures accounted for only 1,435 delays, or 4.4 percent.

Using NYCTA data, Battelle Columbus Laboratory estimated that the reliability of NYCTA cars was about 842 hours MTBF. However, there was great variability among the different models of cars. The older equipment, despite having been in service much longer, was five to ten times more reliable than the newest equipment—the R–44 series cars. For example, the R–36 cars (purchased in 1962) had 4,048 hours MTBF; and the R–38 cars (dating from 1965), had 2,126 hours MTFB.[62] In contrast, MTBF for the new R–44 cars was only 421 hours-or about half that of the fleet as a whole.[63] Preliminary indications are that the newest equipment, the R–46 series now being delivered, have even less low reliability.

This experience suggests that some of the reliability problems experienced by new systems such as PATCO and BART result not so much from train control automation as from the general complexity of the newer transit vehicles, All types of

[61]The R–44 and R–46 cars are equipped with cab signals; but since the wayside equipment associated with cab signaling has not yet been installed, the cars are run with the cab signal units cut out.

[62]The R–36, R–38, and R–44 cars were all purchased from the same manufacturer.

[63]The average age of the NYCTA fleet is 17 years, with almost one-sixth having been in service over 28 years. All of these oldest models had an MTBF greater than that of the R–44 cars.

car equipment have grown more complex over the years. Propulsion motors, suspension systems, door operating mechanisms, air conditioning, and couplers are but a few of the mechanisms that have become more complicated and sophisticated. Thus, ATC equipment may produce reliability problems, not because of automation per se, but because it represents the introduction of one more complex piece of equipment in an already complex vehicle. The general rule of reliability is that as the number of interacting components increases, the overall reliability of the system decreases, The experience of NYCTA, which has no carborne ATC equipment, confirms this point.

ISSUE O–8: MAINTAINABILITY

To what extent does ATC equipment maintainability contribute to the general maintenance problems of transit systems?

ATC equipment is considered by transit managers to be a major maintenance problem, but probably no more so than other types of complex and sophisticated transit equipment. The problem of ATC maintenance is difficult to assess quantitatively because of the scarcity of detailed data and the variety of recordkeeping methods employed by transit systems.

Maintenance of transit system equipment is a never-ending battle. Weather conditions, hard daily use, and the demands of meeting train schedules all tax the ability of equipment to perform as required and increase the pressure to restore equipment to service when failures occur. The promptness with which maintenance is performed and the effectiveness of the repair action play a role almost as important as equipment reliability itself in sustaining the required level of service to transit system patrons, The overall importance of maintenance in the scheme of transit operations is illustrated by the fact that in most systems the maintenance force is equal to or larger than the force required to operate the trains. Maintenance of ATC equipment, because it is vital to the safety and efficiency of train operations, is of special concern.

The influence of ATC equipment maintainability on the general maintenance picture is hard to determine. Most transit systems do not keep detailed and formal records that would allow the maintenance problems of ATC (or any other specific kind of equipment) to be analyzed and evaluated in precise quantitative terms. Shop logs, workmen's time records, and repair tickets are useful as working documents, but they do not lend themselves to treatment as a data base for calculating maintainability statistics such as mean time to restore (MTTR). The following observations, therefore, are based primarily on interviews with transit system maintenance personnel and constitute largely opinion and anecdotal evidence. This is supplemented with a small amount of data obtained from BART and PATCO, where detailed and quantitative maintenance records are kept.

The general feeling among transit system personnel is that ATC equipment poses especially difficult maintenance problems. Because this view is widely held by those intimately acquainted with the maintenance situation, it must be accepted. However, the data from PATCO, and perhaps BART also, do not entirely bear this out. This is not to deny that maintenance of ATC equipment requires substantial effort but simply to suggest that the size of the effort is not disproportionate in relation to that required for other types of transit system equipment of similar complexity and reliability, An examination of the data from PATCO will help to clarify this point.

Table 23 is a summary of maintenance time for several types of equipment in PATCO during a recent 16-week period. Maintenance time is expressed in terms of mean time to restore or repair (MTTR) and as a percentage of the total maintenance effort. For comparison, the frequency of failure for each type of equipment is also shown, expressed as the percentage of total failures,

In terms of both average repair time (MTTR) and proportion of the maintenance effort, ATC equipment is not significantly different from other types of equipment. MTTR is slightly over 3 hours for ATC, the same as for the master controller and only a few minutes longer than for the cam controller or motor generator. It is also significant that the time required for ATC repairs is in the same proportion to the total maintenance effort as ATC failures are to total equipment failures.

Interviews with maintenance personnel from other transit systems suggest, however, that the PATCO situation may not be typical, The experience in these other systems, notably older

TABLE 23.—Maintenance Time for Selected PATCO Car Components

COMPONENT	Number of Failures or Events	Total Repair Time (hours)	Average Repair Time (MTTR) (hours)	Percent of All Maintenance	Percent of All Failures
ATC	284	881	3.1	5.1	5.7
Air Brake	275	636	2.3	3.7	5.5
Cam Controller	288	803	2.8	4.6	5.8
Communication	118	165	1.4	0.9	2.4
Controller	110	270	2.5	1.6	2.2
Coupler	424	582	1.4	3.3	8.5
Master Controllers	17	53	3.1	0.3	0.3
Motor-Generator	168	449	2.7	2.6	3.4
All Corrective Maintenance	5,005	12,007	2.4	69.0	—
Periodic Maintenance	1,213	5,387	4.4	31.0	—

[1]Data are for a 16-week period, July 1–November 1, 1974.
[2]High voltage switches.
[3]Operator's control unit in cab.

FIGURE 58.—Maintenance of Transit Vehicle Truck

systems converting to more automated forms of train control, indicates that ATC equipment takes longer to repair than other kinds of equipment. This is probably true if the comparison is made to conventional mechanical components. It could not be established how ATC repair time compares to that for other kinds of complex electronic equipment, in part because there is relatively little such equipment in use, except for radios and some elements of the propulsion control system.

Several reasons are cited by maintenance personnel to support this view that ATC equipment is difficult to maintain. Troubleshooting and fault isolation are more difficult procedures. It may take a substantial amount of time to confirm the train operator's report of trouble. Some kinds of failure are intermittent; others are difficult to reproduce under shop conditions. Also, the description of the malfunction reported by the operator may be erroneous or imprecise. Once the fault is diagnosed, the repair process may be time-consuming, both because of the type of work required and because of the need to check out additional secondary problems. A recurring problem in electronic maintenance in general, and ATC in particular, is the difficulty in ascertaining the effectiveness of the repair. This is the so-called repeating failure. In BART, for example, it is estimated that about one-third of the cars account for over two-thirds of the repairs; and a car delivered to the shop for a specific repair may be returned one or more times on successive days for the same reason. This has led some maintenance managers to the conclusion that realistic work planning must be based on the assumption that corrective maintenance for ATC equipment will be from 1.25 to 2 times the equipment failure rate,

It is widely agreed that the maintenance of electronic equipment, of which ATC equipment is a prime example, calls for a different type of maintenance skill than conventional transit system equipment. The human factor aspects of this problem will be treated later in a separate issue, but it should be noted here that the qualifications and experience of the shop force have a sizable influence on the success of ATC maintenance operations. Related problems are the shortage of qualified maintenance technicians and the more extensive training required to bring in new personnel or reassign the existing shop force. These manpower problems are especially keen in established transit systems going through a process of installing a new ATC equipment or adding new lines. New systems tend to recognize these problems in advance and make provision to solve them in the preparatory period before inaugurating operations. Even so, this anticipatory action is not always successful, and new systems such as BART have had trouble in acquiring and training a suitable shop staff for electronic maintenance.

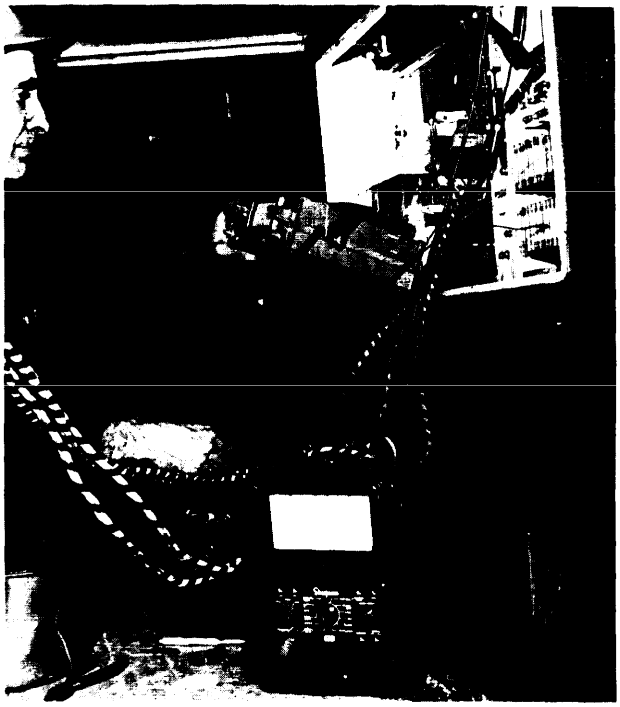

FIGURE 59.-Cab Signal Maintenance

A related problem is that of facilities and shop equipment. The work space and tools required to maintain electronic equipment are very different from that of the conventional car shop. Most transit maintenance is dirty, heavy work that is largely mechanical, Electronic maintenance calls for a facility more like a laboratory or television repair shop. Special tools and test equipment are needed, and many transit systems have had to build such items themselves because of a lack of a suitable version on the general market, Older systems like CTA and MBTA have also had to build new maintenance facilities or remodel existing ones in response to the special needs arising from introduction of cab signals and related ATC equipment. But here again, the problem is not peculiar to ATC but stems from the more general trend in rail rapid transit to convert to a different form of technology.

FIGURE 60.—Car Washer

As a final point, it should be noted that the design of ATC equipment and its placement on transit cars may aggravate the problems of maintenance. Access to equipment cases or individual components within them may be difficult; and the time to remove and replace an item may exceed repair time itself. In some instances, the equipment is not designed modularly so that defective elements can be quickly replaced and the car restored to service.

Repair of electronic equipment while it is in place on the vehicle is generally not an efficient maintenance strategy; but in many cases, the strategy of on-vehicle repair has been forced on maintenance personnel by a lack of spare parts. Nearly all transit maintenance and operating personnel interviewed during this study cited availability of spare parts as a major problem. Several factors seems to be at work here. First, there is the generally low reliability of new equipment; components are wearing out or becoming unserviceable at a much higher rate than anticipated. Second, there has been some instances of inadequate provisioning of spare parts in the initial procurement order. The lead time for replenishing stocks is often long, which tends to exacerbate the spare parts problem once it is detected. Third, some suppliers do not find it profitable to keep a supply of items that may be peculiar to a single transit system or to only a single procurement order by that system, Transit systems, old and new alike, have found it increasingly difficult to locate alternative sources of supply, The shortage of spare parts is not restricted to ATC equipment. It is a general problem in the transit industry, cited here to indicate all the factors that influence the maintainability of train control equipment,

The car availability problems that have plagued the BART system have received widespread attention in the transit industry and in the public at large. Equipment reliability, and often ATC system reliability, is cited as the major cause. Upon closer examination, it appears that maintenance may also be an important part of the problem. A recent management audit of BART (Cresap et al., 1975) stated that maintenance was the prime problem to be solved by BART and recommended that approval for a full 20-hour, 7-day operating schedule be withheld until the maintenance backlog is cleared up and continued operation of the full 450-car fleet could be assured, Fig. 61 is a summary of the maintenance situation that existed in BART from May 1974 to January 1975, roughly the period during which the management audit was conducted. These findings are offered not in order to single out the BART system for special criticism but only to illustrate the impact that maintenance can have on car availability and transit system performance, In this regard, the categories of "Backlogged for Corrective Maintenance" and "Awaiting Parts" are particularly noteworthy, Estimates by BART officials indicate that ATC equipment maintenance makes up 10 to 20 percent of the total maintenance burden, a proportion roughly equivalent to the ratio of ATC failures to all equipment failures.

COST

The costs of automatic train control, both the initial capital cost to design and install ATC equipment and the cost to operate a transit system with ATC, raise several important issues,

In the area of capital cost, there is a need to examine the expense of acquiring an ATC system, in absolute terms and relative to the cost of the whole transit system. It is also important to examine the incremental capital costs associated with increasing the level of automation from a simple ATP system to one including ATO and ATS as well,

With regard to operational cost, the general issue is the comparative expenses of transit systems employing different levels of automation. Within this issue are specific questions relating to manpower and labor cost savings that may be derived from automation. There is also the question of energy savings that may be achieved by the more efficient train operation claimed to result from ATO and ATS,

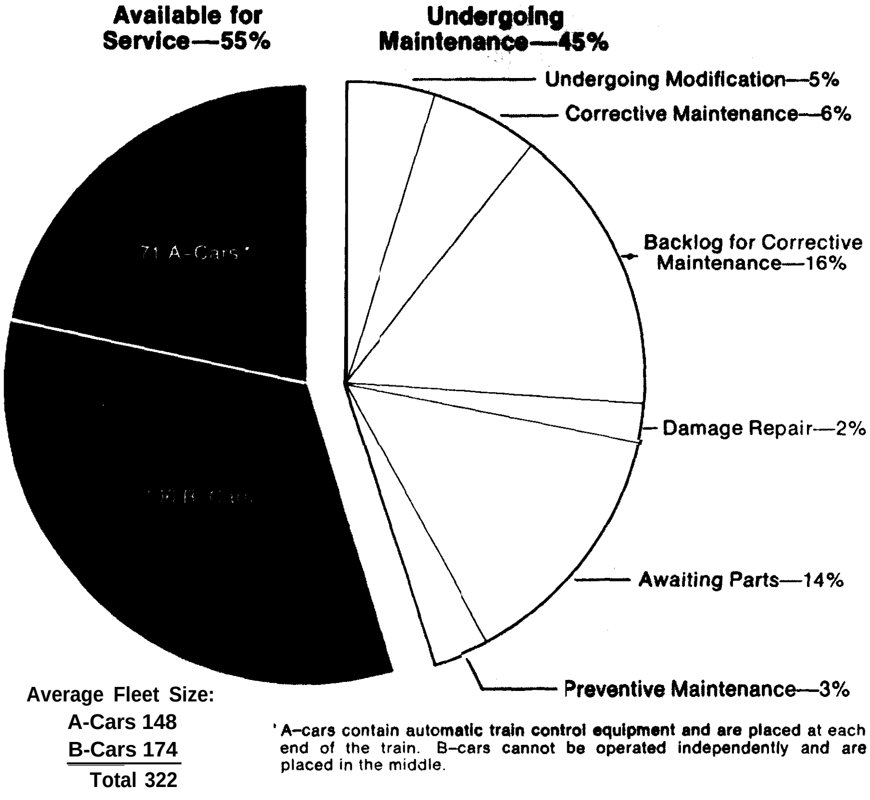

FIGURE 61.—Influence of Maintenance on Car Availability in BART, May 1974–January 1975

Ultimately, the matter of cost reduces the question of whether the greater expense required to acquire an ATC system can be recovered by operational savings over the life of the equipment, This matter is important, not just because of the public funds involved in capital grants and operating subsidies, but also because advocates of automation claim that ATC more than pays for itself in the long run,

ISSUE O–9: CAPITAL COSTS

What are the capital costs of automatic train control ?

ATC equipment costs are roughly 3 to 5 percent of the total capital costs for a rail rapid transit system. Ninety percent or more of the ATC cost is for wayside equipment.

The capital costs of an ATC system are influenced by a number of factors, primarily:

Level of Automation—the number of ATP, ATO, and ATS functions which are automated and the degree of operational sophistication (the number of running speeds, degree of supervisory control, or station stopping accuracy).

System Size **and Configuration—miles** of track, number of interlocking, number of stations and terminals, the number of trains or vehicles operated, and the nature of the train consist (i. e., A and B cars, married pairs, single-car trains, etc.),

Condition of Installation—installation as part of the original construction of the system or as an add-on to a system already in service. (The latter is generally more difficult and expensive.)

Customized Designs—the degree to which a specific ATC installation differs from other ATC designs in use within the system or elsewhere and the degree of custom engineering required to meet local requirements.[64]

Table 24 is a summary of capital costs on transit systems recently built or now under construction, Because of the factors cited above and the effects of inflation, the costs of these systems cannot be directly compared, However, the data do indicate the general range of costs incurred in recent years by transit agencies building completely new systems with advanced levels of ATC.

[64]One supplier of ATC equipment estimated that special engineering of just the speed regulation and station stopping equipment for a new installation can cost between $100,000 and $200,000.

TABLE 24.-Capital Costs in New Transit Systems

	PATCO	BART	WMATA	MARTA	MTA (Baltimore)
INITIAL SERVICE	1969	1972	1976	1979	1981
TOTAL SYSTEM					
Cost ($ million)	1135	1,586	24,650	[2]2,100	3450
Miles	14	71	98	50	[3]15
Cost/Mi. ($ million)	9.6	22.3	47.4	42	330
VEHICLES					
Cost ($ million)	15	143	199	NA[4]	NA[4]
Number	75	450	556	338	NA[4]
Cost/Vehicle ($)	200,000	318,000	358,000	NA[4]	NA[4]
TRAIN CONTROL					
Automation Level[6]	ATP, ATO	ATP, ATO, ATS	ATP, ATO, ATS	ATP, ATO, ATS	ATP, ATO, ATS
Cost ($ million)	4.5	[5]40.5	[2]100	NA[4]	[3]25

[1]Includes capital cost of new construction and equipment, renovation, and estimated value of preexisting right-of-way and structures

[2]Current estimate, cost by completion date will probably be higher.

[3] Estimate for phase I, 15-mile partial system (1970 dollars).

[4]Not available.

[5]Includes additional work; original bid was $26,2 million.

[6]ATS here means computer-aided Central control.

Since there are so many local and temporal factors at work, and because so few new systems have been built, historical data on procurements in such systems as PATCO, BART, and WMATA and projections for MARTA and MTA do not provide a meaningful picture of the capital cost of ATC. A different perspective is provided by Table 25, which contains estimated capital costs based on interviews with manufacturers and consultants concerning the current prices (1975 dollars) of major ATC system components.

Table 25 separates ATC equipment into two categories: carborne equipment and wayside equipment (including central control and ATS equipment). Within each category, successive levels of automation are identified and priced. The prevailing view in the transit industry today is that cab signals, overspeed protection, route interlocking, a modest supervisory system, and the associated communications equipment represent the minimum ATC system that will be installed. Thus, the first entries in the vehicle and wayside categories of table 25 should be considered a baseline system. Additional features incur additional costs as indicated.

To obtain an estimate of the total cost of a typical ATC installation, consider the example of a hypothetical transit system consisting of 50 miles of double track (100 single-track miles) and zOO carborne controlled units (400 cars operating as married pairs with one ATC package per pair). The total cost of a baseline ATC installation (ATP only) in such a transit system would be approximately $59.5 million ($57.5 million for wayside and $2 million for carborne equipment) .65 This would be a system with a level of automation roughly equivalent to the MBTA Red Line or the CTA West-South Line. The addition of ATO (the second entry in the wayside and carborne categories of table 25) would raise the cost to almost $70 million ($65 million wayside, $4.5 million carborne), This would be a system resembling PATCO. The addition of ATS, to build a system with a level of automation similar to BART, would raise the capital cost to $87 million ($82.5 million wayside, $4.5 million carborne). Note that the addition of ATS does not increase the cost of carborne ATC equipment since virtually all the additional equipment needed for ATS is in the central control facility.

While the absolute cost of an ATC system may be large, ranging up to $100 million or more for a large system with a high level of automation, its

[65] These estimates assume values for carborne and wayside equipment costs in the middle of the ranges given in table 25.

TABLE 25.—Cost Estimates for **ATC Equipment**

ELEMENT	UNIT OF MEASURE	APPROXIMATE UNIT COST
CARBORNE EQUIPMENT		
Cab signaling and overspeed protection	Controlled Unit[2]	$ 9,000-11,000
Above, plus speed maintaining, precision stopping, performance level adjustment, and train identification	Controlled Unit[2]	18,000-25,000
WAYSIDE EQUIPMENT		
Cab signaling, overspeed protection, route interlocking, data transmission, modest supervisory system	Single-Track Mile	500.000-650,000
Above, plus precision stopping, performance level adjustment, and train identification	Single-Track Mile	550,000 -750! 000
Above, plus sophisticated ATS with computerized control	Single-Track Mile	750,000-900,000

[1] 1975 dollars
[2] A controlled unit may be more than one vehicle. e.g., a married pair of cars typically has only one set of ATC equipment.

(SOURCE: Battelle from manufacturer and consultant interviews.)

cost relative to the total capital cost of the system is low. A rail rapid transit system typically costs $30 million to $45 million per double-track mile to build. Transit vehicles cost in the range of $200,000 to $350,000 each, depending upon their size and complexity. On this basis, wayside ATC equipment represents something on the order to 3 to 6 percent of the cost per track mile. Carborne ATC accounts for 5 to 12 percent of vehicle cost.

Returning to the example of the hypothetical system, the total cost would be about $2 billion.[66] The ATC system, depending upon the level of automation selected, would run between $60 million and $87 million, or 3 to 5 percent of the total capital cost, Note that the cost increment associated

[66](50 double-track miles X $35 million per mile) + (400 cars, i.e., 200 married pairs, x $300,000) = $1.88 billion + $0.12 billion = $2 billion.

Section of **BART Transbay Tube**

BART Elevated Guideway

WMATA Pentagon Station

WMATA Judiciary Square Station

FIGURE 62.—Transit System Construction

with selection of an ATC system with a high level of automation instead of a baseline system with ATP alone, would amount to only 2 percent or so of the total capital cost of the transit system. Note also that the bulk of the expense, either for a baseline or a highly automated ATC system, lies in wayside equipment—90 percent or more.

ISSUE 0–10: OPERATIONAL COST

How do the operating costs of systems with automatic train operation compare to those of systems where trains are run manually?

The costs of operating trains are somewhat lower in systems with ATO, but the maintenance costs are higher. In general, ATO reduces the proportion of personnel-related costs in operating a transit system.

One of the purported advantages of automatic train control (particularly automatic train operation) is that it can reduce the operating costs of a transit system. This reduction would be brought about primarily by decreasing the number of personnel needed to operate the system. The question of workforce reduction is thus a pivotal issue that needs to be examined from several aspects. The purpose here is to look at operating cost in general terms to provide a background for the specific discussions of workforce reduction in the two following issues.

Table 26 is an analysis of operating costs for the most recent year in five transit systems, Since these systems vary greatly in size and service level, the data are normalized by expressing cost in terms of dollars per revenue car mile and as percentages of total operating expenses for each system. Costs are allocated to three categories: transportation, maintenance, and administration, The transportation category includes all costs incurred in providing passenger service. Payroll and fringe benefits for train crews, central control personnel, station attendants, and supervisors are the largest components; but the category also includes electric power costs and all other expenses associated with transit operations.[67] Maintenance includes all personnel-related costs for vehicle, track, signal, and structures maintenance as well as the cost of material and supplies. Administration is made up of all expenses associated with management, support, and administrative services and all general expenses not directly attributable to either transit operations or maintenance,

The five systems are arrayed in an order that represents an increasing level of automation, from left to right, but the principal distinction is between NYCTA, CTA, and MBTA with conductors on the trains and PATCO and BART without. Note, however, that technology is not the only factor determining the size of the train crew, Local labor

[67] Transit police expenses have been excluded since not all systems have an internal police force.

TABLE 26.—Summary of Rail Rapid Transit Operating Costs

	NYCTA (1973/74)	CTA (1974)	MBTA (1974)	PATCO (1974)	BART (1974/75)
OPERATING COST ($/revenue car mile)					
Transportation	1.05	0.95	2.15	0.72	0.89
Maintenance	0.62	0.44	1.45	0.59	11.33
Administration	0.26	0.15	1.22	0.16	0.30
Total	1.93	1.54	4.82	1.47	12,52
PERCENT OF OPERATING COST					
Transportation	55	62	45	49	36
Maintenance	32	29	30	40	52
Administration	13	9	25	11	12
RATIO OF MAINTENANCE COST TO TRANSPORTATION COST	0.59	0.44	0.68	0.82	1.48
SALARIES. WAGES & BENEFITS AS PERCENTAGE OF OPERATING COST	82	82	80	64	74

I For stable year operation, BART forecasts a maintenance cost of about $0,83 per revenue car mile, with transportation and administrative expenses remaining a t present levels, If the reduction of maintenance is achieved, the total cost per revenue car mile would be $2.02 and the maintenance-transportation cost ratio would he 0,93.

agreements and operating philosophy also play strong roles. Thus, any cost differences among these systems are not purely the result of train control automation.

Examination of the revenue costs per car mile reveals a wide variation among the five systems," with no clear-cut pattern. PATCO, a system with ATO and a single train operator, has the lowest overall operating cost;[68] but BART, which is equally automated in the area of ATO, has costs substantially higher than any system except MBTA.

[68]The PATCO figures are somewhat deflated in the area of transportation and administration. PATCO stations are largely unattended, while all the other systems have station attendants. Many administrative functions normally carried out by a transit agency are, in the case of PATCO, accomplished by its parent organization, the Delaware River Port Authority. If allowance is made for these factors, the transportation-related costs of PATCO might be on the order of 80 to 85 cents per revenue car mile and the administrative costs 20 to 25 cents per revenue car mile.

Nevertheless, it does appear that transportation costs are lowest in the two systems with ATO. It also appears that maintenance costs are somewhat higher than in systems with manually operated trains. In the case of BART, this is probably a reflection of the general maintenance problems that have plagued the system and not a specific effect of ATO.

The reciprocal relationship of maintenance and transportation costs appears most pronounced when they are expressed as percentages of the total operating cost of the respective systems. As the proportion of transportation costs goes down, the maintenance proportion rises; and the sum of the two is a roughly constant 80–90 percent of the whole.[69] The tendency of the relative cost of maintenance to in-

[69]This generalization does not hold true for MBTA, where the percentage of administrative costs is unusually high and where absolute costs are about double those of any other system,

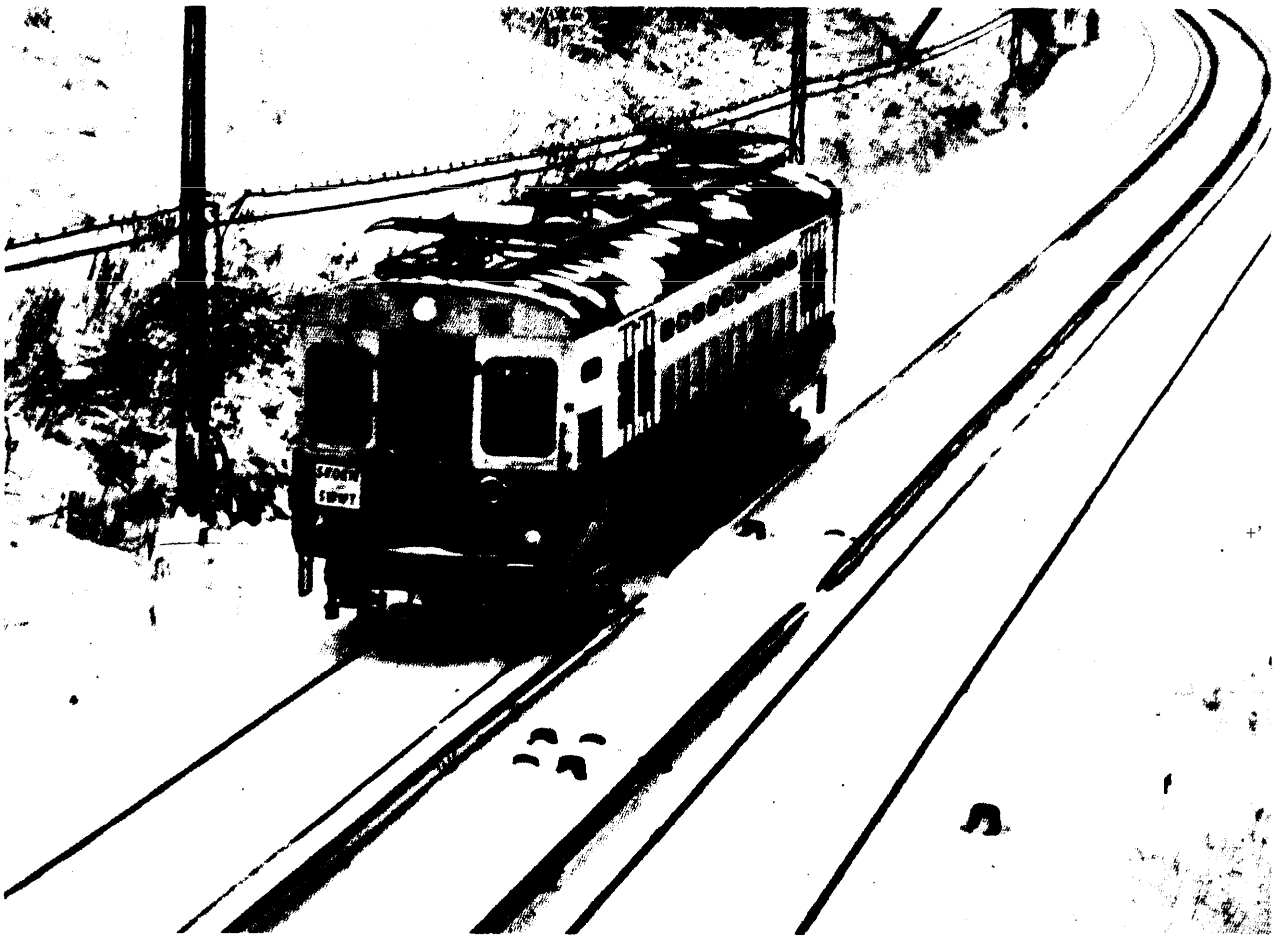

FIGURE 63.—Winter on the Skokie Swift Line

crease as a function of automation also appears when maintenance cost is expressed as a ratio of transportation cost.

Another apparent, and logically expected, effect of automatic train operation is the lower proportion of payroll-related costs in PATCO and BART. Labor accounts for 80 to 82 percent of operating cost in the systems with manually operated trains and two- or three-man crews. In PATCO, labor costs are only about two-thirds of total cost—partly due to one-man operation and partly due to the absence of station attendants. In BART, the percentage is higher, although still lower than NYCTA, CTA, and MBTA. BART officials forecast that the labor component will drop to something like 65 to 70 percent when the debugging period is passed and the maintenance situation becomes more normal.

While some of these observed differences undoubtedly arise from causes not related to automation, it does appear that ATO (insofar as it leads to a reduction of train-crew size) has the effect of lowering labor cost and, perhaps, overall operating expense, This conclusion must remain tentative at this point because the data are limited to such a few cases. However, it deserves further examination in the following issues, which deal more specifically with the manpower effects of ATO,

ISSUE 0–11: WORKFORCE REDUCTION

Does automatic train controJ lead to a reduction of the workforce?

Automation of train operation functions, permitting reduction to a one-man train crew, leads to small but significant workforce savings. Further automation, but short of total automation, has little effect.

As a concept, automation implies the replacement of human labor with machines. In some cases, automation results simply in lessening the workload for operating personnel without changing the manning level of the system. In other cases, it may be possible to replace a human operator altogether--either by assigning all functions to machines or by consolidating several partially automated functions into a smaller number of operator positions. The potential economic advantages of automation are large, Rapid transit is a labor-intensive system, in which personnel costs (salaries and benefits) typically account for 65 to 85 cents of every dollar of operating expense. Clearly, even a small manpower reduction of 10–15 percent would have enormous leverage and might make the difference between an operating deficit and breaking even,

Historically, rail rapid transit has pursued a course of consolidation by successively reducing the number of conductors in the train crew, In the early days, conductors were assigned to each car or pair of cars to collect fares and operate the doors. As fare collection was transferred to stations and as semiautomatic and power-assisted door mechanisms were introduced, the conductor workforce was reduced to one per train, with even greater relative reductions brought about by running longer trains. In newer systems such as PATCO and BART, the conductor has been eliminated altogether, and the door operation function has been transferred to the train operator (PATCO) or automated entirely (BART). The ultimate step is a fully automated system like AIRTRANS, which operates unmanned vehicles.

Table 27 shows the general effect on the workforce produced by various levels of ATC. Representative transit systems are listed by increasing level of automation. Because these transit systems vary greatly in size and organizational structure, the data have been normalized by expressing workforce as the ratio of operations and maintenance personnel to vehicles. Personnel responsible for administrative, support, planning, developmental engineering, station operation, station maintenance and police activities are excluded in order to confine the comparison to the area most directly affected by ATC.

For MBTA, NYCTA, and CTA, where automation is the least and the train crew is two or three, the employee/vehicle ratio is between 3.1 and 2.4. In PATCO, where ATO has permitted reduction of the train crew to one, the ratio is lower than in MBTA and NYCTA but higher than in CTA, The PATCO ratio might be lower if PATCO were more nearly the same size as the others. There are undoubtedly economies of scale in a large organization that cannot be obtained in a transit property with only 75 vehicles and 203 operations and maintenance employees.

The more advanced level of automation represented by BART does not result in a manpower

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TABLE 27.—Effect of Automation on Size of Workforce

SYSTEM[1]	TRAIN CREW	O&M EMPLOYEES	TRANSIT VEHICLES	EMPLOYEES PER VEHICLE
MBTA	[3]2 – 3	1,063	354	3.0
NYCTA	2	21,045	6,681	3.1
CTA	2	2,594	1,094	2.4
PATCO	1	203	75	2.7
HART (1974/75)	1	1,000	350	2.9
BART (Stable Year)[4]	1	1,192	450	2.6
AIRTRANS (1974)	0	142	68	2,1
AIRTRANS (Stable Year)[4]	0	122	68	1.8

[1] All data are for the most recently completed operational year.
[2] Includes only personnel to operate and maintain trains, with immediate supervisors.
[3] Train crew consists of motorman and one train guard for each pair of cars,
[4] After debugging and transition to fill] operational status.

reduction, BART at present has an employee/vehicle ratio about equal to MBTA or NYCTA. In projected stable-year operation, the ratio will decline to a level comparable to that of PATCO, The reason for the rather high rate in BART at present is apparently connected to the problem of equipment reliability, which necessitates a large maintenance force. Further examination of this point will be deferred to the next issue, where the composition of the workforce in BART and other systems will be analyzed,

The employee/vehicle ratio for AIRTRANS, a fully automated system with unmanned vehicles, is about the same as PATCO, where there is a one-man train crew, AIRTRANS is, however, a new system still undergoing operational shakedown. The present operating force includes 36 passenger-service employees required to help patrons find their way around the airport. It is anticipated that the need for such employees will decrease once better signing has been installed. It is also expected that the maintenance force will be reduced as debugging and break-in of the equipment is completed and more operating experience is gained, It is anticipated that the total of O&M employees would go down to about 122 in a stable year, producing an employee/vehicle ratio of 1.8, a figure substantially lower than that of any manned system,

From these data it appears that ATO, insofar as it allows consolidation of conductor and motorman functions in a single train operator position, will produce a small but significant manpower saving.[70] Automation to levels beyond the minimum required for such consolidation, but short of full automation, does not seem to lead to further manpower savings because of offsetting increases in the required maintenance force,

ISSUE 0-12: WORKFORCE DISTRIBUTION

What effect does automatic train control have on the composition and distribution of the workforce ?

As the degree of automation increases, the number of operation employees goes down, but the number of maintenance employees goes up. The net result is a shift in the balance of the workforce without a substantial decrease in the total O&M force.

[70] Transit system professionals point out that automation is only one factor influencing the size of the train crew. Union agreements and work rules, especially in established transit systems, may play a part in keeping the conductor on the train even though the train could be satisfactorily operated by one person at the existing level of automation. In some circumstances, transit system management officials may also conclude that the conductor position should be retained for reason of passenger safety in emergencies or as a way of offering information and other assistance to patrons on long trains.

CTA Train With Conductor

BART Train Without Conductor

FIGURE 64.—Reduction of Train Crew

In the discussion of the preceding issue, it was concluded that automatic train operation (ATO), insofar as it permits reducing the train crew to one, produces a small decrease in the total O&M workforce. This decrease, however, is not commensurate with the number of conductor positions eliminated, It is therefore necessary to examine the composition and distribution of the workforce at various levels of automation to see what countervailing effects are at work.

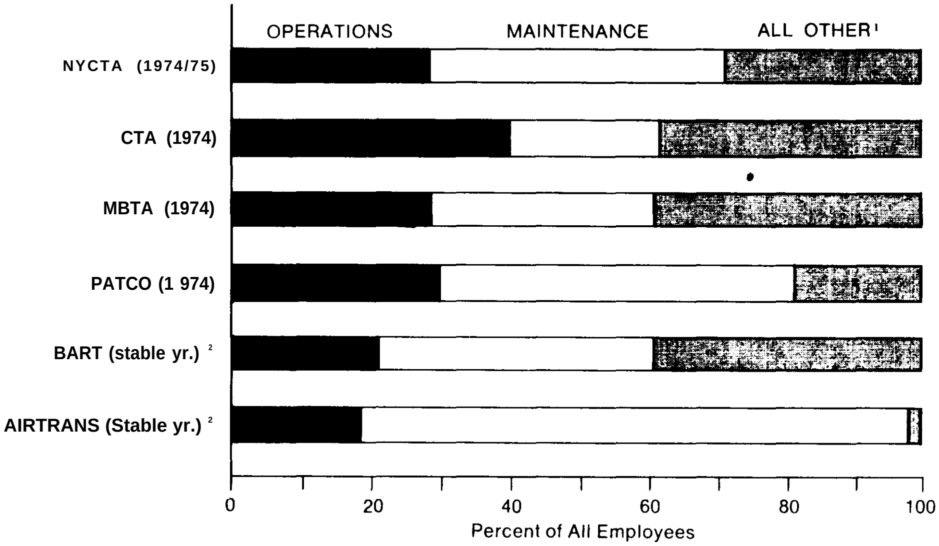
Figure 65 shows the relative size of the operations and maintenance forces in five transit systems. To illustrate the effect of full automation (i.e., elimination of all on-board personnel), similar figures are also given for AIRTRANS, even though it is not a true rail rapid transit system. Operations employees are all those necessary to operate trains-dispatchers, trainmasters, stationmasters, towermen, central controllers, and yard motormen as well as the train crew itself. Maintenance personnel include the employees in car shops, and those needed to maintain way, power, and signals. The size of the operations and maintenance forces is expressed as a percentage of all employees for the respective transit systems.[71]

While there is considerable variation in the data, there does appear to be a discernible trend. Reading from top to bottom, as train operation generally becomes more automated, the proportion of operations employees declines while the proportion of maintenance employees shows a corresponding increase. It appears that ATO results primarily in a shift of the balance of the O&M workforce but without significantly changing its size in relation to the total workforce. More specifically, as conductors and finally the operator are taken off the train, almost equal numbers of new jobs are created in the car shops and wayside maintenance crews.

A more detailed analysis is presented in table 28, where the workforce in the operations and maintenance departments is expressed in terms of the number of employees per car. The number of operations employees per car generally declines from 1.2–1.4 for systems with manual train operation and a crew of two (NYCTA, CTA, and MBTA) to 0.3 for a fully automated system (AIRTRANS). PATCO and BART, with a train crew of one, fall about midway between. At the same time, the maintenance force increases from 0.8 per car in CTA to 1.8–2.0 for BART and AIRTRANS in the current year.[72] The same trend shows up even more clearly in the ratio of maintenance to operations employees, where there is a threefol I to ten felt I difference between manned systems without ATO (NYCTA and CTA) and the unmanned AIRTRANS system, with PATCO and BART falling at roughly proportional intermediate points.

[71] Transit police and construction personnel are excluded.

[72] Estimates of stable year operations for both systems project a decrease in the ratio of maintenance employees per car to 1.5–1.7, a figure comparable to PATCO.



1. Excludes transt police and construction personnel
2 Estimated staffing when debugging is completed and the system becomes fully operational

FIGURE 65.—Proportion of Operations and Maintenance Employees in Total Workforce

TABLE 28.-Analysis of Operations and Maintenance Workforce

	NYCTA (1974/75)	CTA (1974)	MBTA (1974)	PATCO (1974)	BART 74/75	BART S.Y.[1]	AIRTRANS 74	AIRTRANS S.Y.[1]
Total Cars in Fleet	6,681	1,094	354	75	350	450	68	68
O&M Employees	21,045	2,370	1,063	203	1,000	1,192	142	122
Operations Employees	8,350	1,540	482	75	315	415	22	22
Maintenance Employees	12,695	830	581	128	684	777	120	100
O&M Empl./Car	3.1	2.2	3.0	2.7	2.9	2.6	2.1	1.8
Ops. Empl/Car	1.2	1.4	1.4	1.0	0.9	0.9	0.3	0.3
Maint. Empl/Car	1.9	0.8	1.6	1.7	2.0	1.7	1.8	1.5
Maint. Empl./Opr. Empl.	1.5	0.5	1.2	1.7	2.2	1.9	5.5	4.5

[1]Estimated stable year operation.
[2]Traincrew, dispatchers, towermen, central control, and yard motormen.
[3]Maintenance of vehicles, way, power, and signals.

The differences among these systems are not solely attributable to ATC. A large share of the maintenance force (67–93 percent) is not concerned with ATC equipment but with other carborne and wayside components, which also tend to need more maintenance as the transit system becomes more complex or equipment and structures grow older. Still, the percentage of maintenance employees involved in ATC-related activities shows a general increase proportionate to the level of automation.

In NYCTA, with no carborne ATO equipment and all ATP in the wayside, it is estimated that 10 percent of the maintenance force performs ATC-related work (primarily signal maintenance). The estimated figure for CTA is about 5 percent, about half for wayside equipment and half for cab signals. For MBTA the figure is now 7 percent, but expected to increase as cab signals are installed on other lines. PATCO, with cabs-signaled ATP and ATO, has about 15 percent of the maintenance force dedicated to ATC (9 percent wayside, 6 percent cars), For BART, the ATC position of the maintenance force is now about 31 percent (18 percent for wayside and central ATS equipment, 13 percent for cars)--a distribution that is expected to remain essentially the same when stable-year operation is attained. From these data, it appears that the progression from ATP (either wayside or cab signals) to ATP and ATO results in a doubling of the percentage of the maintenance force assigned to ATC activities. The increase to a system with ATP, ATO, and ATS (if BART is typical) causes the percentage to double again.

If the PATCO and BART cases are assumed to be representative of the manpower shifts that result from automation of the train control system, it is possible to draw some tentative conclusions about cost savings attributable to ATC. For PATCO, the incorporation of ATO made it possible to run the trains with a single operator, resulting in the elimination of about 45 conductor positions. At the same time, about 15 additional shop and wayside personnel were required to maintain ATC equipment. This is a net of 30 fewer employees. However, the pay rate for personnel skilled in ATC maintenance is generally higher than that for conductors. Assuming a pay differential of 20 percent for ATC maintenance workers, the effective saving in payroll costs reduces to about 25 positions, or roughly 9 percent of the annual payroll. Following a similar line of reasoning, the BART ATC system eliminated the need for about 315 conductors, but added about 200 to the maintenance force, a net of 115 fewer positions.[73] Adjusting for maintenance pay differential, this is equivalent to a saving of about 75 positions, or roughly 4 percent of the annual payroll. Since labor costs are about three-quarters of all system operating costs, 'these calculations suggest that automatic train operation with a crew of one offers the potential to reduce operating costs somewhere between 3 and 6 percent per year.

[73]The BART estimate assumes stable-year staffing levels.

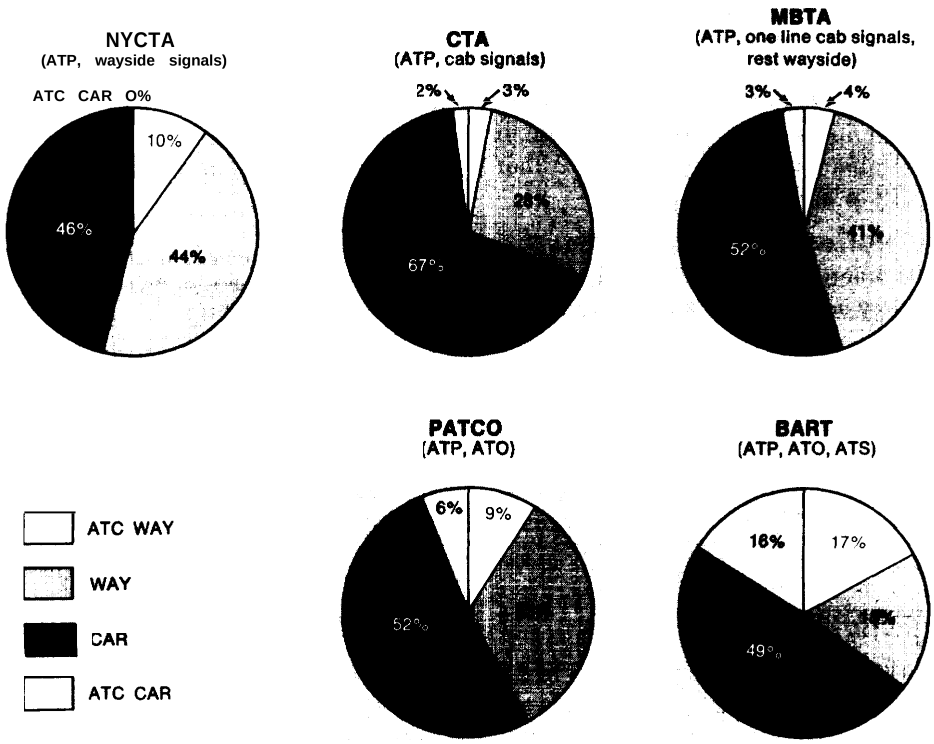


FIGURE 66.—Distribution of Maintenance Force as a Function of Automation

ISSUE 6–13: ENERGY COST

Does ATC result in any energy savings in transit operations?

Electric power consumption rates for systems with and without ATC do not show any differences attributable to the mode of train control. If there are any energy savings due to ATC, they are probably so small as to be overwhelmed by other operational factors such as speed and the power-weight ratio of vehicles.

One of the arguments often advanced for automatic train control is that ATO and ATS can lead to a more efficient mode of train operation and, hence, lower energy consumption. It is asserted that, in an automatic system, trains can be run at more uniform headways and at predetermined speed-distance patterns, which provide lower maximum speeds and more uniform accelerating and braking rates. This yields a lower power consumption per car mile as a direct effect. The more uniform spacing of trains brought about by operating at optimum conditions also has an equalizing effect on the passenger load of trains, and in turn produces more energy savings as a secondary benefit. More uniform headways also shorten layover times at terminals, permitting a reduction in the number of trains operated and still further energy savings. (Irvin and Asmus, 1968)

Theoretically, this argument is sound; but it is difficult to test its practical validity and to assess the magnitude of energy savings that might actually be achieved in revenue operations with various forms of ATC. Table 29 is a summary of the energy consumption in the five transit systems considered in this study. Energy usage is expressed in terms of kilowatt-hours per revenue car mile and per passenger mile. The latter figure is perhaps the better index for comparing energy consumption among the five systems because it is independent of vehicle seating capacity and load factor.

Note that the power consumption figures are systemwide totals, including traction power and all other uses such as vehicle lighting and air conditioning, station operation (lighting, escalators, etc.), parking lots, and maintenance facilities. A purer form of comparison would be the energy required for traction power alone, but such figures could not be accurately derived from the records of some systems. Thus, there is some distortion of the data due to factors other than train operation, but their influence is probably not large since traction power represents the dominant share of all energy use (typically three-quarters or more) .[74]

The data in table 29 do not indicate differences among transit systems that appear to be related to ATC. With the exception of CTA, the energy consumption per passenger mile is about the same for all systems, regardless of the level of automation. In short, there is no conclusive evidence that ATC saves energy, at least when energy use is measured at the overall system level.

[74] In BART, for example, traction power amounts to about 75 percent of all power use. In PATCO, traction power is 85 to 90 percent of the total.

TABLE 29.—Rail Rapid Transit Energy Consumption

ENERGY CONSUMPTION	NYCTA (1973/74)	CTA (1974)	MBTA (1974)	PATCO (1974)	BART[2] (1974/75)
ANNUAL KILOWATT-HOURS (million)	2055.0	256.2	102.4	39.3	197.9
ANNUAL REVENUE CAR MILES (million)	320.6	46.8	10.3	4.3	21.6
ANNUAL PASSENGER MILES (million)	35480,()	775.2	[4]263.2	95.0	446.4
KWH/REV. CAR MILE	6.4	5.2	9.9	9.2	9.2
KWH/PASSENGER MILE	0.38	0.33	0.39	0.41	0.44

[1] Power consumed for all purposes (traction, station operation, shops, etc.).
[2] Estimate based on operating data for July 1974 to January 1975.
[3] Estimate based on average trip length of 5 miles
[4] Estimate based on average trip length of 3,1 miles.

There may indeed be energy savings due to ATC, but they cannot be discerned by the methods employed here. In all probability they are small and masked by several other factors which account for most of the observed differences among the five systems. For example, these transit systems differ greatly in their maximum operating speed and average line speed. The two systems with ATO (PATCO and BART) also happen to run trains at higher speeds. Since power consumption varies directly as a function of speed. the possible energy savings due to ATC in PATCO and BART are probably offset by the increased energy required to run trains at 70–75 mph.

The weight of the vehicle has a profound effect on the amount of traction power required to move trains. There is great variation among transit systems in the weight of vehicles, and this factor alone probably accounts for most of the difference in power consumption. In this regard, it is significant that CTA (with 20- to 24-ton cars) has the lowest level of energy use and PATCO (39-ton cars) has one of the highest.

It should also be noted that several other factors influence power consumption. Among these are the aerodynamic properties of vehicles[75], route characteristics, the steepness of grades, and station spacing. Any one of these factors is probably sufficient to counterbalance any energy conservation that might be attainable through ATC. Collectively, they confound the picture of energy use in operating transit systems to such a degree that ATC-related benefits, if any, are impossible to isolate.

[75]The amount of aerodynamic resistance to be overcome varies according to whether the train is operating in a tunnel, on elevated structure, at grade, or in a cut.

HUMAN FACTORS

Man, as operator and supervisor, has traditionally played a vital part in rail rapid transit train control systems. The train crew, tower operators, dispatchers, and central supervisory personnel of a conventional, manually operated transit system make up a highly skilled team, whose functions are to assure the safety and efficiency of passenger service. As specific tasks, formerly carried out manually, are assigned to automatic components, the human role is diminished quantitatively—in the sense that there is less work for man to do. At the same time, however, the place of humans in the system acquires even greater importance in some respects. The tasks remaining for man in transit systems with ATP, ATO, and ATS are generally those that are considered either impractical to automate or so vital to system operation that human attention is mandatory. This suggests that, along with the diminishing of workload that comes with automation, there comes a qualitative change in the role of man. While certain vital functions are re-

FIGURE 67.—State-of-the-Art Car

tained by man, he becomes less an operational element of the system and more a monitor, overseer, and back-up for automatic elements, which themselves carry out the direct functions of train control.

Up to this point in the discussion of operational experience with ATC, automation has been treated primarily in terms of machine performance and engineering concerns. To complete the picture, it is now necessary to examine the inverse subjects of the role of man and the effects that automation produces upon the humans who, perforce, remain an integral part of the train control system. There are two major questions here. First, there is the need to examine whether man is used effectively and prudently in systems with various levels of ATC. What use is made of man's performance capabilities? Is adequate attention given to human needs as operator and supervisor? Is man well integrated into the system? The second major concern is the consequences that have resulted from the application of automation in transit systems. Specific matters of interest are changes in working conditions and job qualifications for transit system employees and the secondary effects that ATC may produce for the riding public using the transit system,

ISSUE O–14: THE HUMAN ROLE

Is effective use made of man in systems with ATC?

In some cases, new transit systems with ATC do not make effective use of the human operator to back up or enhance automatic system performance, and human involvement in normally automatic processes tends to degrade performance, primarily in terms of speed, headway, and level of service. In systems now under development, there **seems to be a greater concern for the role of man and for making the** ATC system more amenable to human intervention.

In considering the role of humans in systems with automatic train control, it is necessary to distinguish among the parts played by man in each of the major functional categories: train protection, train operation, train supervision, and communication.

In train protection (ATP), the motormen (and conductors, if there are any) customarily perform very few functions, except in a back-up or emergency capacity. Nearly all transit systems have either wayside or cab signal equipment that automatically assures train separation and prevents overspeed, The human operator's tasks are track surveillance (for detecting persons and obstacles on the right-of-way or as a back-up to track circuits for detecting other trains) and emergency braking in unusual circumstances that the ATP system is not designed to detect. The operator also acts to restore the system to operation in the event of ATP system failure, performing such tasks as emergency brake release, key-by, or manual route request. Since the operator is backing up a highly reliable system, there are significant problems in maintaining proper vigilance and alertness, There is also considerable risk of human error in cases where the ATP system is not functioning properly or has been deliberately bypassed (as when closing in on a disabled train).

FIGURE 68.—Student Conductors Training on the Job

In the area of train operation (ATO) there is wide variation among transit systems in the tasks assigned to the on-board operator, In NYCTA, CTA, and MBTA (except the Red line) all train operation functions are performed manually. In PATCO, only door operation and train starting are manual in normal circumstances. In BART, all train operation is automatic. The role of the on-board operator in systems with ATO is mainly limited to monitoring automatic equipment performance, acting as a back-up in the event of malfunction or emergency, and—in some cases—adjusting the performance level of the ATO system (e.g., by modifying speed-acceleration profiles or by ordering the train to run by a station without stopping). The major human performance problems that have been encountered in regard to ATO are the effectiveness (and safety) of manual intervention in normally automated processes and the adequacy of the controls and displays provided to the operator for purposes of monitoring or manual takeover.

FIGURE 69.—Motorman at Work

Train supervision embraces a number of diverse functions, mostly carried out at a remote, centrally located facility. Here, too, there is wide variation among transit systems in the degree of automation. At one extreme virtually all functions except train dispatching are manual operations. At the other extreme, scheduling, dispatching, route selection, traffic regulation, and documentation of events are carried out by automatic devices either wholly or primarily. Because the supervisory facility is the nerve center of the transit system, there can be significant workload problems for supervisory personnel, particularly during rush hours or emergency situations. These problems may be aggravated in systems with ATS if there is a breakdown of automatic equipment or the need for extensive human intervention in response to unusual conditions to which the computers are not programed to respond. The major difficulties that have been encountered in systems with ATS are the quality and timeliness of information available to central control personnel, the flexibility of automatic system response in abnormal or emergency conditions, and the ability of humans to assume the burden of making and implementing decisions in areas normally assigned to machines.

While there has been some automation of the communication process in the newer transit systems, primarily in the area of data transmission, the major thrust of technological innovation has been to-provide train crews and central supervisors

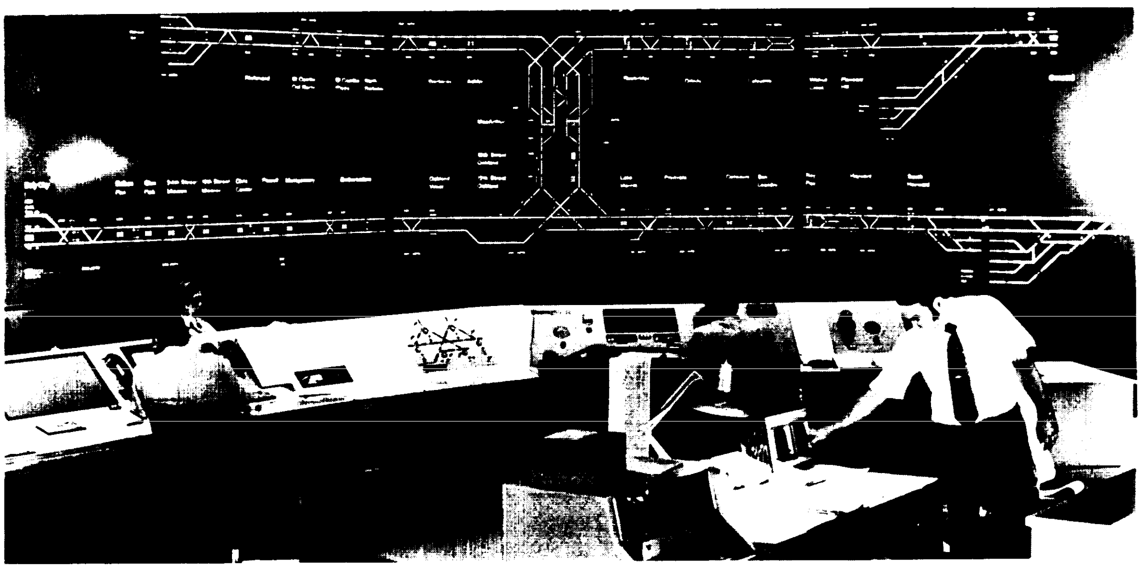


FIGURE 70.—Line Supervisors

with more extensive means of voice communication. The major problems encountered have been how to manage communication networks of increased size and complexity, how to limit unnecessary or excessive exchanges (chatter), and how to implement various modes of selective and general address. There has also been a general concern about the ability of improved communication systems to compensate for the fewer number of on-board personnel in providing information and instructions to passengers in special or emergency situations and in affording passengers a way of communicating with remotely located transit system employees.

Table 30 is a summary of the allocation of tasks to men and machines in several operating and developmental transit systems. The table also indicates man-machine allocations in AIRTRANS which, although not a true rail rapid transit system, may be considered representative of the extent that present technology can go in achieving a fully automated train control system. The systems have been arrayed in a generally increasing order of automa-

TABLE 30.—Man and Machine Roles in Rail Rapid Transit Systems

KEY: A = Automated; M = Manual; — = Not provided

TRANSIT SYSTEM	SITUATION	Track Surveillance (ATP)	Train Separation (ATP)	Route Interlocking (ATP)	Overspeed Protection (ATP)	Velocity Regulation (ATO)	Station Stopping (ATO)	Door Monitoring and Control (ATO)	Performance Level Modification (ATO/ATS)	Train Dispatching (ATS)	Schedule Monitoring & Adjustment (ATS)
NYCTA	Normal	M	A	A	A	M	M	M	M	A	M
	Abnormal[1]	M	A	A	A	M	M	M	M	M	M
	Emergency[2]	M	M	AIM	AIM	M	M	M	—	M	M
CTA	Normal	M	A	A	A	M	M	M	M	A	M
	Abnormal	M	A	A	A	M	M	M	M	M	M
	Emergency	M	M	AIM	A/M	M	M	M	—	M	M
MBTA[3]	Normal	M	A	A	A	A	M	M	M	A	M
	Abnormal	M	A	A	A	A	M	M	M	M	M
	Emergency	M	M	A/M	AIM	M	M	M	—	M	M
PATCO	Normal	M	A	A	A	A	A	M	M	A	M
	Abnormal	M	A	A	A	M	M	M	M	M	M
	Emergency	M	M	AIM	AIM	M	M	M	—	M	M
MTA[4] (Baltimore)	Normal	M	A	A	A	A	A	M	M	A	A
	Abnormal	M	A	A	A	A/M	AIM	M	M	M	M
	Emergency	M	M	A/M	AIM	M	M	M	—	M	M
WMATA[4]	Normal	M	A	A	A	A	A	A	A	A	A
	Abnormal	M	A	A	A	AIM	AIM	AIM	A	A	A
	Emergency	M	M	AIM	AIM	M	M	M	—	M	M
MARTA[4]	Normal	M	A	A	A	A	A	A	A	A	A
	Abnormal	M	A	A	A	A	A	M	AIM	A/M	AIM
	Emergency	M	M	AIM	AIM	M	M	M	—	M	M
BART	Normal	M	A	A	A	A	A ,	A	A	A	A
	Abnormal	M	A	A	A	A	A	AIM	A	A	A
	Emergency	M	M	AIM	A/M	M	M	M	—	M	M
AIRTRANS	Normal	—	A	A	A	A	A	A	A	A	A
	Abnormal	—	A	A	A	A	A	—	A	A	A
	Emergency	M	AIM	AIM	A/M	M	M	M	—	M	M

[1] Moderate delays, bad weather, unusually heavy demand
[2] Major delays, accidents, failure of critical equipment.
[3] Red Line only.
[4] Under development, not yet operational.

tion to facilitate seeing the overall pattern of replacement of the human operator by automated devices,

It can be seen that the general effect of increased automation is for machines to assume a greater and greater share of operational functions in normal situations and in certain off-normal conditions, but not in emergency conditions. At every level of automation, man remains the primary means of sustaining system operations under extreme conditions and the back-up element in the event of equipment failure. On board the train, the result of automation is diminished importance of operating skills for the train crewman and increased emphasis on the ability to monitor automatic equipment functions. Man's primary job is not running the train but overseeing train operation and intervening when necessary. At central control facilities, automation results in more routine decisionmaking being allocated to machines, which monitor traffic flow, adjust schedules to compensate for irregularities, and alert supervisory personnel when special action outside the bounds of computer programs is required.

The conversion of train control from a manual to an automated process has produced problems on both sides of the man-machine interface. These problems arise not from any inherent inadequacy of automation technology as such; almost any level of automation is a technically viable solution. Instead, the problems stem from within the design of particular systems and from the way in which the man-machine interface is engineered. The following are specific examples of successful and unsuccessful aspects of automated equipment design drawn from the experience of transit systems with operational ATC systems.

Train Protection

ATP equipment has proven to be highly reliable; but, in a way, this reliability has also created problems, Train operators tend to take ATP for granted. ATP equipment operates so well so much of the time that the operator is inclined to neglect his responsibilities as a monitor and back-up and to forget what he must do to safeguard the train when ATP equipment is inoperative or when it has been purposely bypassed. The general experience of transit systems is that accidents tend to occur when train operators revert to visual observation and rules of the road because the normal automatic methods of train protection are inoperative.[76]

A related problem arising from ATP (and from highly automated forms of train operation) is that of vigilance. At first glance, it would appear that relieving the train operator of most routine and burdensome tasks would produce a near-ideal situation, in which he would be free to concentrate on a few surveillance and monitoring tasks and perform excellently in that role, Unfortunately, the result is almost always the contrary. Given too little to do, one tends to lose vigilance and to exhibit problems of motivation. For a person to remain vigilant, the events to be observed must occur with reasonable frequency. To keep a person motivated, the assigned tasks must be demanding enough to prevent boredom and meaningful enough to engage attention. "Make-work" tasks, or those perceived as such, are not satisfactory. The individual must feel that he has a useful and important role to play. Duties should not appear to be vestigial to machines or compensatory for their inadequacies. (TSC, 1974)

Train Operation

One of the operator's primary duties in systems with ATO is to intervene whenever either equipment performance or operational conditions fall outside prescribed limits. In some cases, however, the act of manual intervention results in a further degradation of system performance. For example, in BART where trains are normally operated automatically, the design of the system effectively precludes the operator from assuming manual control without causing a delay in service. Train speed in a manual mode of operation is limited to so percent of the speed allowable under ATO. Thus, manual takeover inevitably results in a slowing of the train and, as a consequence, following trains also. Furthermore, taking over manual control requires that the train first be brought to a full stop, thus compounding the delay. There is no technological or human impediment to operating transit vehicles manually at high speed or to changing from an automatic to a manual mode while the train is in

[76] The collision of MBTA trains in August 1975 occurred in just such a circumstance. A train operating under line-of-sight rules entered a tunnel and struck a leading train waiting to be keyed by a defective trip stop, A third train, also operating under line-of-sight rules, struck the rear of the second train about 2 minutes later.

motion. The PATCO ATO system permits a man to operate the train at full speed, and the WMATA system will also, because it was recognized during the design process that such was a desirable way for man to augment the performance of an automated system.

The PATCO system also incorporates other features that promote effective cooperation between man and machine in maintaining the desired level of service. One of the train operator's responsibilities is to help complete the trip on time in case the ATO equipment should fail. Because failure of this sort is not expected to occur often, it is necessary to devise a means for the human operator to maintain his manual skills so as to be able to perform at his best when needed. In PATCO this is assured by an operating rule that requires each operator to make one trip per day in the manual running mode. The skill thus maintained also helps in other circumstances, such as when rails are slippery. ATO system performance is not as good as in manual operation in this condition. Thus, a combination of equipment design and procedures permits the system to make effective use of the human operator as a means of enhancing the performance of automated equipment. This lesson is being applied in the design of new systems such as WMATA and MTA.

The display of information to the train operator is an aspect of design that has been somewhat neglected in transit systems. Speed regulation is an important operator duty on manually operated trains, and yet there is no speedometer in the cab to tell the operator his actual speed, except in systems that have cab signals or ATO. Even with cab signals, the human factors of information display are not always given proper attention. For example, the BART operator's console originally contained only an indicator of actual speed. The command speed, with which actual speed is to be compared, was not displayed, A command speed indication was later added, but as a digital readout.[77] This form of display does not facilitate the operator's speed monitoring task since it requires making comparisons between two digital indicators, each of which may be changing rapidly. There is a considerable body of human factor research that indicates digital displays are difficult to interpret for trend and rate of change, factors which are as important as speed itself in monitoring the relation of command and actual speed, An analog indicator, such as a conventional automobile speedometer, is generally a much more effective and informative display for such purposes.

[77] The WMATA operator's console has indicators of command and actual speed, but also in digital form-an example of learning part, but not all, of the lesson to be gained from the experience of others.

Train Supervision

Train supervision is an area where, historically, there has been very little automation, except for train dispatching. All operating transit systems, except BART, supervise train movement by largely manual methods. In BART, the central computer handles tasks such as traffic regulation (schedule adjustment) and performance level modification. The train control systems under development in Washington, Atlanta, and Baltimore will incorporate similarly automated forms of train supervision,

ATS poses several design problems relating to human factors. One important concern is what to do when the computer fails, An abrupt change from automatic to manual supervision can cause major disruption of service and may even affect the safety of transit operations. Attention is being given to this problem in the design of the new systems (WMATA, MARTA, and MTA) and in planning for the addition of ATS to NYCTA, One solution is to design ATS equipment so that it does not fail abruptly and absolutely, but gracefully (i.e., in slow stages) and with sufficient coast time for human supervisors to assess the situation and decide on an appropriate course of action, New systems are also providing for intermediate levels of operation between manual and automatic. These modes allow the ATS system to operate under manual inputs or to serve as an information processing aid to human decisionmaking. The ATS system for MARTA is being implemented in two stages — semiautomated first and fully automatic later. After the second stage is implemented, the first will be retained as a back-up mode, a training device, and a means for central control personnel to retain manual skills,

Central supervisory systems, both manual and automated, also exhibit the deficiencies of display design noted earlier in connection with operator's cab equipment. Some systems do not have any form of central display board (model board) to allow supervisors to monitor the progress of trains. Personnel are required to form a mental picture of the situation on the line by monitoring verbal reports from trainmen, towermen, or station dispatchers and by reading pengraphs or other such nonpictorial indicators. In systems that do have model boards, the supervisor's task is somewhat easier since there is a large diagrammatic representation of the track layout with lighted indicators to show train location. Sometimes, however, the model board does not indicate track occupancy block-by-block but for longer sections of track. If there is a stalled train, for example, the supervisor may know from looking at the board only that it is between one station and another but not precisely where. If a following train is ordered to close up and push the stalled train to a station or siding, the central supervisor cannot follow the progress of this operation by means of the display board. The central control facilities being designed for WMATA and MARTA will incorporate special displays that allow supervisors to "zoom in" on selected sections of track or to call up display modes of differing levels of detail to suit the task in hand.

This brief review of human factors problems associated with existing ATC installations is not intended to be exhaustive nor to single out particular systems for praise or criticism. The purpose is only to indicate the general range of problems encountered and to illustrate the need for more attention to human factors in the design of ATC systems.

Neither the recently built systems with ATC (PATCO and BART) nor those now under development have had a formal human factors program. This is not to suggest that the role of man was not considered by the planners and engineers, but there is no evidence that an explicit and systematic analysis of human factors was made a part of the design process. An exception to this general finding is MARTA, where periodic design reviews are being conducted by a team from DOT Transportation Systems Center. This team includes human factors specialists, and their examination of proposed MARTA designs has led to several suggestions for integrating man more effectively into the system.

Proper attention to the role of the individual in ATC systems can have substantial benefits for transit operations. If automation is approached not as a question of how to replace the operator in the train control system but as how to make best use of this highly valuable human resource, the safety and efficiency of ATC systems can be greatly improved. Man is particularly valuable as an element of a real-time control system because of his versatility, flexibility of response, and ability to deal with the unexpected or the unusual. To attain these advantages, however, man must be made a partner in the system. His job must not be treated as an afterthought or as the residue of functions that equipment engineers have found technically or economically impractical to automate.

ISSUE 0-15: EFFECTS OF AUTOMATION ON EMPLOYEES AND PASSENGERS

What impacts does train control automation have on transit system employees and on passengers?

For employees, especially maintenance workers, ATC results in higher job qualifications, more extensive training, and more demanding performance requirements. For passengers, the effects are negligible except insofar as ATC influences the quality of service.

There have been no studies of the specific effects of automation in rail rapid transit systems either for employees or passengers, despite the obvious importance of these topics in the overall assessment of the social impacts of new technology. What follows, therefore, is based on anecdotal evidence and interviews with transit system managers. The applicability of these observations to transit systems as a whole is hard to determine. The experience of each operating agency is somewhat unique in that labor conditions, workforce makeup, personnel policies, and operating history vary from site to site. New transit systems, like PATCO and BART, have no previous experience with nonautomated operation against which to judge the effects of ATC. The installation of ATC equipment in older systems, such as MBTA or CTA, is both limited in scope and relatively recent. For these reasons, comparisons among systems or within systems for before-and-after effects cannot be made. The comments offered here are therefore general in nature and confined to those effects most frequently cited by system operators and managers.

Operations Employees

A primary result of the automation of train operation functions is a general shift in the skill requirements for trainmen. The motor skills, coordination, and knowledge of signals and rules needed to operate a train manually are still important qualifications, but they are no longer the sole concerns. The role of ATO system monitoring and back-up places additional requirements on the operator—knowledge of how the system operates, ability to interpret failure indices, skill in diagnostic techniques, and an understanding of how aid automatic system operation without necessarily assuming full manual control. Thus, the repertory of operator performance tends to be larger in systems with ATO, and the modes of response more varied.

The selection criteria for train operators do not appear to differ substantially for systems with or without ATO, and they are about the same for bus operators in those systems that operate both modes of transit.[78] The general requirements are physical fitness and the common standards of employability (checks of police record, retail credit, and previous employment). Educational background (above a certain minimum level of schooling) and aptitude tests do not figure in the selection process, either for manual or automatic systems. Thus, ATC does not appear to alter the basic level of qualification for initial employment as a train operator.

While employment qualifications are unaffected by automation, there does seem to be a longer training program for operators in systems with ATC. The longer program results not so much from a need for more intensive training as from a need to cover a greater range of subjects. This is probably a direct consequence of the wider repertory of job skills required of operators in systems with ATO.

Since manual train operation is not a regular part of the job, systems with ATO have found it necessary to provide opportunities for practice and to test operators periodically to determine if manual skills have been retained. There is no evidence that train operator performance standards are more exacting at one level of automation than at any other, except insofar as systems with ATO call for a wider variety of job knowledge.

Train supervisory personnel appear to be very little affected by ATS. Selection criteria, training requirements, and job performance for dispatchers and line supervisors are about the same for all the rapid transit systems surveyed. The BART train control room, because of the use of computers for supervisory functions, has employees versed in computer operation and maintenance-a class of employee not found in other transit systems. For these employees the skill, training, and performance requirements are, of course, unique and, because of their special expertise, somewhat higher than other types of supervisory employees.

Maintenance Employees

The major impact of ATC upon transit system employees is for maintenance workers, Traditionally, the signal maintainer was a person who had good mechanical skills and a basic understanding of the theory and operation of electromechanical devices (especially relays). This worker tended to be a generalist, in the sense that he was capable of dealing with all types of signal system failure and repair, The installation of more advanced forms of ATC and the technological shift to solid-state logic and printed circuit boards has brought about a change in the type of maintenance employee needed and in the organization of the maintenance force. New and more specialized skills are required, and the organization has become more hierarchical and segregated into specialty occupations. Transit vehicle maintenance has come to be more and more like aircraft maintenance.

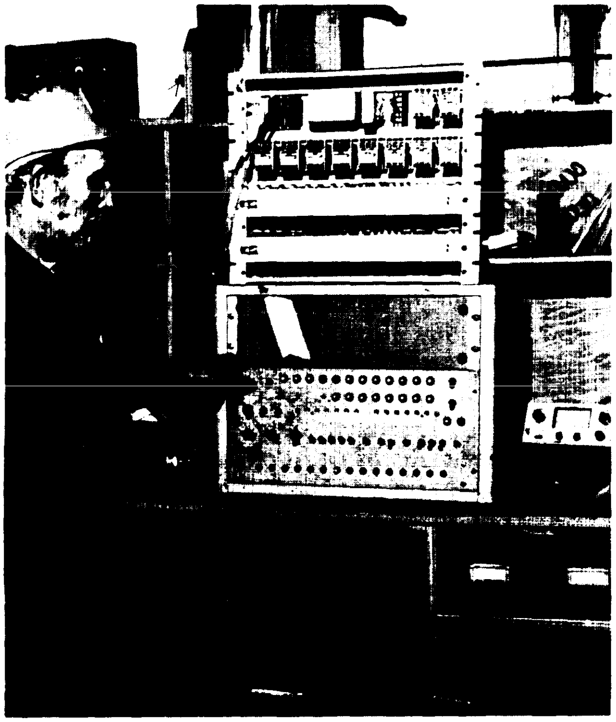
The electronic nature of ATC equipment has made the diagnosis and repair of malfunctions a more complex and demanding task. Typically, this task is divided among maintenance specialists, with the first-line maintenance worker responsible only for identification of the fault and replacement of the defective module as a whole. Isolation of the fault to the component level may not be the responsibility of the first-line worker. This part of the maintenance task may be assigned to a second level of worker, who may repair or replace the failed component or who may isolate the fault further and pass a particular element along to a third level of maintenance worker specializing in that type of repair.

An additional task assigned to maintenance personnel in systems with ATC is that of configuration control. During the period following the introduction of new equipment or the opening of a new system, equipment modifications are made frequently. Because of the strong interdependency of

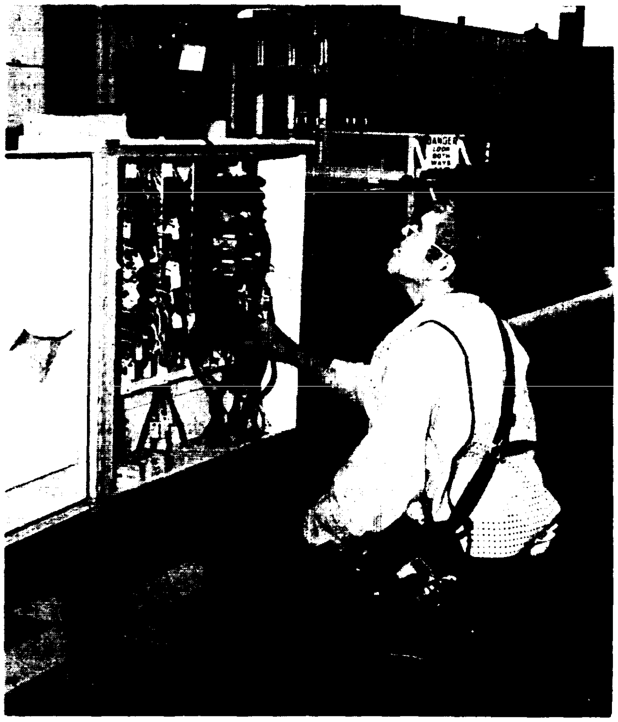
[78] WMATA, which now operates a bus system and is preparing to start rapid transit operations, is seeking to recruit train operatora from its bus driver force.

Track Gang

Electronic Repairmen



Cab Signal Maintainer



Wayside Equipment Maintainer

FIGURE 71.—Transit System Maintenance Workers

components that characterizes most new and sophisticated transit system equipment (of which ATC equipment is only an example), it is becoming more and more necessary to maintain extensive and accurate records of exactly what equipment is installed on a given car at a given time. The maintainer must spend more time with service bulletins and maintenance documents in order to keep abreast of configuration changes.

In the area of maintenance, new transit systems have some special human factors problems that are not shared by established systems. In an established transit system there is already a maintenance force in being and procedures and techniques for maintaining the equipment are familiar to all. The introduction of a new item, such as cab signals, disrupts the pattern somewhat but only for a small part of the maintenance force since the rest of the equipment is unchanged. In a new transit system, everything is new. The equipment itself may be a new design or, at least, new in its specific application. Workmen and supervisors are likely to be inexperienced in maintaining transit equipment-of all types, not just ATC. Procedures are untested and unrefined by experience. The facilities themselves are usually sized to handle normal workloads rather than the huge influx of failures and repairs that may occur during start-up. Manufacturers' representatives may be working alongside the maintenance staff making equipment modifications or assisting in debugging. The training system for preparing new maintenance workers may not yet be functioning smoothly. These conditions may result in an impairment of worker efficiency, quality control problems, and—if they persist--a lowering of worker morale.

There are also long-term effects on the maintenance force produced by ATC. The size and organization of the workforce, as noted earlier, are different. Generally more workers are needed, with special skills, and with a more elaborate division of responsibilities. The qualifications for employment as an ATC technician are usually higher and more specialized than for other types of transit maintenance workers. The period of training, both in classrooms and on the job, is often longer. The performance requirements on the job may also be more stringent, Existing transit systems that are converting to some form of ATC have had difficulty in finding qualified personnel, and efforts to recruit trainees within the existing transportation or maintenance forces have not always been successful. Bringing in new personnel from the outside is an alternative, but the training period may be longer since they are unfamiliar with transit equipment-a disadvantage that may be partly offset by the better basic skills typically found in personnel already familiar with electronic maintenance and specifically recruited for that purpose. New transit systems, of course, have little choice but to recruit and train an entirely new maintenance force since there is no existing labor surplus of ATC technicians, either locally or nationally, to draw on.

It should be noted that ATC generally leads to an upgrading of the maintenance force. Since ATC is an addition to all the other types of transit equipment, it increases, not decreases, the number of jobs available, The pay levels for this kind of work tend to be higher than for other types of transit maintenance; and, to the extent that ATC technicians are recruited from within an existing workforce, it offers employees opportunities for advancement.

Passengers

The transit passenger typically has very little interest in the technical details of the system—ATC or otherwise. One transit system manager expressed it thus:

> People use a mass transit system to get from a point of origin to a point of destination, and they want to do it quickly, reliably, comfortably and economically. The train is nothing more than a people box, The system designers' job is to create a system which will enable that people box to traverse the transit corridor rapidly and reliably, day after day after day. The passenger doesn't care—has no interest in knowing—whether the train is controlled by a master centralized computer, or localized control—whether it is powered by AC or DC motors or by little squirrels running around cages-whether it operates on standard gauge rails or extra wide rails—whether those rails are supported on timber cross ties or concrete cross ties. The passenger does care about being able to board his train every day at a preestablished time, riding in a clean and comfortable environment, arriving at his destination without being ruffled either physically or emotionally, completing the trip as quickly as is reasonably possible, and accomplishing it all at a fare which he considers to be reasonable. (Johnston, 1974)

The impact of ATC on passenger acceptance of the system would thus appear to be minimal, unless the ATC system is the specific cause of service delays-and publicly identified as such, Some transit system managers expressed the view that public confidence in a highly automated system might be lower than for a conventional system, especially during the start-up period or following some other period of operational difficulty, However, it was also believed that, once the public becomes accustomed to the system and if performance is reasonably reliable, apprehension about automation would subside. It is very difficult to gauge public opinion in this matter for there have been no studies directed to the topic of automation in transit operations. Furthermore, public comment on new systems, such as BART, tends to be in response to specific events and often does not grasp the essential technical issues.

There is a widely held view in the transit industry that a completely automated train control system without an on-board operator is not a viable proposition. Passenger safety in emergency conditions demands the presence of a transit system employee to control the situation, to evacuate the train, and to lead passengers to safety. The AIRTRANS system has experienced problems in this regard. Passengers in unattended vehicles become apprehensive when the train stops somewhere other than at a station, even though there is no real or apparent emergency. There have been cases of passengers leaving the train and walking on the tracks, causing a shutdown of the system until they can be reboarded or led to a station. It is also believed that passengers derive a sense of security from the presence of an on-board operator, both as a source of aid in emergencies and as a protection against personal attack or crime. Unmanned vehicles are also considered to present operational problems. Without an operator to control car door closure, the passengers may adversely affect headways and capacity because of the variability in dwell time introduced by passenger-actuated doors, Systems with unmanned vehicles (and, to some extent, those with one-man trains) have also found that passengers have difficulty in obtaining information about train routes and schedules. To accommodate passengers, it has been necessary to install more extensive" signing and public announcement devices and, in the case of AIRTRANS, to hire additional station employees to provide passenger information and assistance. The human factors of system design and operation in relation to passengers is a matter that acquires increased importance as the level of train control automation increases and the level of vehicle manning declines,

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