Driven, Attended, and Fully Automated Transit: Qualitative Comparison

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Three levels of automation of line haul, grade-separated, urban transit systems ("Metros") are identified for comparison: driven, attended, and fully automated. Comparisons are made among these levels in eight areas of service, safety, and dependability for line haul, grade-separated transit applications. Attended and fully automated systems nearly eliminate the human errors of a driven system. They also offer shorter headways, thus increasing capacity and service, allowing smaller facilities, or both. The stopping accuracies of attended and fully automated systems allow the use of platform doors, dramatically improving platform safety. These systems can have other benefits, such as reducing insurance premiums, minimizing operational disruptions, and providing a more pleasant waiting room environment. The ride comfort of the two automated levels can also be improved over that of driven systems. Fully automated transit outperforms both driven and attended systems in making schedule modifications, providing off-peak service, and managing failures. It also offers inherent resources for creating a more efficient administration of the system.

Much of the current discussion about line haul rapid transit in North America has concentrated on vehicle hardware (i.e., light versus heavy rail, rubber versus steel wheels, etc.). There is, however, a technical concern that is parallel and related, but often less visible: the level of automation of a system.

In this "high-tech" age, when half the homes in North America contain computers, use of automation has been relatively slow in coming to rapid transit systems. Originally, when many rail metros were first built, operations were performed manually, most often by using visual driving rules. Although trials of automatic electric block signals and trip stops date back to the 1860s and 1880s, it was not until World War II that color light automatic block signals, enforced by track trips (to enforce safe stopping), were routinely installed. This was the first instance in which automation overrode the function of the train's on-board operator.

It was the opening of the San Francisco Bay Area Rapid Transit (BART) system in September 1972, however, that marked the start of major new strides in the automation of urban transit metros. Although BART was originally intended to be a totally driverless system, it never reached that goal. Not until almost 11 years later, in May 1983, did the world's first fully automated (driverless) line haul urban transit system enter public service, in Lille, France. Two and a half years after that, the first major automated guideway transit (AGT) system in North America opened in Vancouver, Canada. In the United States the commitment to build the first line haul urban AGT system was made by the Los Angeles County Transit Commission on May 25, 1988. This system is scheduled to open in 1993.

Much has been written about how these fully automated systems are designed and operate, but comparisons among various transit concepts are frequently intermingled with questions of vehicle design, specific applications, cost comparisons, and so on. The purpose of this paper is to describe, in general terms, the progression of technical benefits claimed by increased levels of automation in the train control of grade-separated, line haul metros. Each level has progressively greater requirements on the redundancy of vehicle subsystems and the remote monitoring and control capabilities of the system. Only through an integrated understanding of all such design requirements and benefits can a proper, detailed cost-benefit tradeoff be made for any specific application.

A quantitative analysis of these benefits would require a much larger report. Furthermore, because fully automated line haul transit systems are still so new, the jury may still be out on some of the more subjective projections of the benefits of automation.

LEVELS OF TRAIN CONTROL AUTOMATION

The progression of automation in the train control of urban transit systems is subdivided here into three easily perceived categories.

Manual Systems

- *Driven* A one- or two-person on-board crew is responsible at all times for applying propulsion and brakes and for operating the doors. On some properties a limited degree of automation is used for safety. In these cases, automatic train protection (ATP) functions will override the crew's actions if they ignore certain safe procedures. Driven systems are typical of older rapid transit systems, such as those in Chicago and New York.
- *Attended* A crew member must be present to start the train, usually simply by closing the doors. He must also drive the train manually in the event of most system failures. Otherwise, the train's velocity between and door openings at stations are automatically controlled. The crew member may be an operator in the front cab, as in Paris and most newer systems (e.g., San Francisco's BART, systems in Atlanta and

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Scarborough) or can be a conductor/ticket checker in the passenger area (e.g., London Docklands).

Automated Guideway Transit

- *Fully Automated* No crew member is needed on board for normal and most failure recovery operations. These fully automated, grade-separated, line haul urban systems will be referred to herein as automated line haul transit (ALT). Lille and Vancouver are the only operational examples of ALT in the world at this time.

COMPOUNDING OF BENEFITS FROM AUTOMATION

There is a general concept that recurs throughout the following discussion of transit system characteristics. That concept will be referred to as the compounding of benefits from automation. This compounding of benefits occurs when the automation of one function facilitates a practical implementation of some other beneficial function or leads to potential cost savings in some other area.

Perhaps the best example of compounding of benefits on ALT systems evolves from an opportunity for more frequent trains at any given speed than is possible on driven systems. More frequent trains open up several opportunities for the operator of the system. Capacity can be increased, platform waits can be minimized, and smaller stations or vehicles can be utilized. This is an example of how a major improvement in a train control technical function ("separation") can provide a compounding of benefits in system characteristics that are directly visible to the public: higher service, lower capital cost, and lower visual intrusion. This improvement is discussed in greater detail in the later subsection on shorter headway.

There are also examples in which the automation of a train control function provides a compounding of benefits to other train control functions. For example, in any system, if a redundant or noncritical component fails on a vehicle, and that failure is recorded at central control, the affected train could be replaced at the end of the line. On driven and attended systems, however, this step is achieved only after communications have been made among central control, line supervisors, arriving and departing crews, and yard transfer crews (hostlers). Rather than be burdened with those procedures, central control personnel might leave the train in service and make a note for the maintenance department to schedule the repairs for that evening. In so doing, they may be risking an operational blockage from additional, and perhaps compounding, failures.

In contrast, in ALT systems the train with the failure can be replaced through simple keyboard inputs at central control, if spares in the fleet are available. The train would return to the maintenance yard automatically, where it might be repaired and returned to service before the day is out. To achieve this result, the fully automated vehicles must be equipped with more redundancy (to minimize disabling vehicle failures) and more detailed "health"-monitoring equipment (to detect the onset of problems) than is normally provided on driven or attended systems. Indeed, system/train interfaces become extremely critical to proper operation, and different automatic train supervision (ATS) is required, in comparison to that used with manual systems. In this example, automated fault detection in fully automated systems can trigger repairs within hours of a failure because of the fully automatic routing of trains. Even if the same level of automated fault detection were available in a driven or attended vehicle, achievement of an immediate response and maximum advantage of the detection would depend on a voice communication link and the availability of personnel.

Thus, although a more extensive communications infrastructure may not be unique to ALT, it is a logical tool that normally accompanies all such systems and offers more return on its investment than it would in manual systems. Through this communications infrastructure, ALT systems typically receive more compounding of opportunities and benefits from automation than do driven or attended systems. Several other examples of this compounding are mentioned in this paper.

The counterargument to this compounding of benefits concept is that the increased complexity of automation can be an added source of breakdowns (from causes that include computer malfunctions), with attendant disruptions to service and increased maintenance. It should be noted, however, that although there may be "teething problems" with the introduction of any new technology, the long-term resolution of the dichotomy between compounding of benefits and breakdowns from complexity lies in bottom-line operational experience. Some preliminary evidence is available from the world's first two ALT systems, and it favors compounding of benefits. For example,

- Lille's productivity per employee (146,000 passengers per employee per year) is close to double the average productivity of driven and attended North American systems.
- Vancouver's system is being extended to new stations, and Lille has opened a new ALT line this year. Both cities are continuing plans for other extensions, new lines, or both. In particular, it should be noted that Lille plans to replace an older yet successful LRT line with a third ALT line.
- The Lille maintenance facility is open only five days a week during conventional business hours, even though patronage is 50 percent higher than originally projected.

COMPARISONS OF PERFORMANCE CHARACTERISTICS

In general, there are eight performance areas in which a differentiation can be made between the three levels of automated train control. They are summarized in Table 1 and discussed in the sections that follow.

Elimination of Human Error from Train Movements

The elimination of human error from train movement was the original reason for introducing automation to transit. Decision-making actions that could result in errors by train operators and control tower personnel have been slowly replaced over the years with fail-safe devices. Initially these devices were pure hardware, but with the advent of voting

TABLE 1 PERFORMANCE COMPARISONS AMONG THREE ATC LEVELS

Factor	ATC Functions[a]	Best Performance		
		Driven	Attended	ALT[b]
1. Elimination of human error from train movements	P.1–3	*	**	***
2. Shorter headway	P.1		**	***
3. Platform benefits	P.4; O.2, 6		*	***
4. Ride comfort	O.1		***	***
5. Schedule modification	S.3			***
6. Off-peak service	S.1, 2			***
7. Failure management	S.5			***
8. Efficient administration	S.4, 6, 7	*	**	***

NOTE: * = some; ** = many; *** = most.
[a]Listed in Appendix A.
[b]Fully automated system, as defined in text.

microprocessors, fail-safe hardware-software combinations are now being used. Recently, fail-safe software has been applied to urban rapid transit (*1*).

Even though the fail-safe design requirement is normally not subject to tradeoffs with other design requirements, it is frequently confused with reliability. Reliability minimizes the frequency of failures. In contrast, fail-safe design ensures that virtually none of those failures, whatever their frequency, will create unsafe conditions. For example, the mechanical steering mechanism in an automobile is very reliable, but when it fails, the condition is almost certain to be unsafe. The vital relays used in the signal systems of railroad and transit properties also have very high reliabilities, yet they, too, may fail. In contrast, however, and more importantly, the design of vital relays and the restrictions on their installation and use virtually guarantee that no unsafe signal can be sent from the relay. Thus, given all the very infrequent failures that could occur in a vital relay, the probability that any one of those failures would be unsafe is so small (smaller than the probability of the failure itself occurring) that it is considered negligible.

In many older Metro systems the ATP system is very similar to that on railroads. A fail-safe signal is given to the train's operator or a switch-interlocking control person (or to both), but there is no insurance against human error, which is the most prevalent single factor in transit accidents. Full ATP can be added to driven systems and is inherent in attended and ALT systems. In systems with full ATP, human error as a safety hazard is virtually eliminated through fail-safe checks on the system operators in driven systems and by automatic fail-safe operation in attended and ALT systems.

Shorter Headways

Headway is the time between the successive arrivals of trains at a station. It is one of the most important parameters in the design of a transit system because within certain limits, shorter headways yield some combination of

- Increased capacity;
- Increased service (shorter waits);
- Shorter stations; and
- Smaller-diameter tunnels, narrower guideways, and tighter curves.

This last point encompasses several assumptions. Vehicle passenger capacity, for example, is proportional to gross floor area (typically, one passenger "place" is 5.4 gross vehicle floor area) (*2*). Tunnel diameters are a function of vehicle widths, and guideway widths are proportional to vehicle widths. Frequently, narrower vehicles are also shorter in length, resulting in closer bolsters, tighter turning radii, and smaller chording and nosing impacts on dynamic envelopes.

Perhaps more than in any other performance item discussed here, the design of short headways into ALT systems shows a compounding of benefits from automation. Driven and attended systems could be fitted with ATP systems that allow relatively short, safe headways at cruise speeds, but the determination of a system's minimum safe headway (MSH) is limited by the maneuvers and dwells of successive trains at on-line stations. Fully automated systems have shorter MSHs than manual ones because they utilize either a safe stopping velocity profile in each fixed block (as opposed to a single speed limit) or a moving block control system. Furthermore, transit systems cannot operate exactly at their MSH. Variances in the performance of the vehicles and the delays that can be imposed by ill, confused, or inconsiderate passengers require a margin to be added to the MSH of any automated or manual system. In manual systems an additional, larger time margin may be required to allow for variations in human responses, especially for driven transit systems. Thus the smallest achievable operating headways in transit are those on ALT systems, where 60 to 70 sec can be achieved with 50-mph line speeds. In contrast, driven systems at the same 50-mph speed with on-line station stops would normally be limited to 90 sec or more.

Attended systems can be designed to achieve the same low headways of fully automated systems but typically have not been, even on new systems. The reasons for this are not evident but appear to stem from the relative similarity between attended and driven systems. This similarity leads to acceptance of the small capital cost savings of longer headways (see Appendix C for a fully automated example) on the basis of the obvious rationale of driven systems: the longer the train, the more passengers one operator can transport. This rea-

soning becomes especially forceful when these trains are compared with the alternative of having the operator drive buses. With longer trains there is less need for shorter headways. Attended systems (light rail in particular) may also contend with automobile traffic at grade crossing or in mixed traffic. Although these locations may be limited in number, the existence of only one creates the weakest link of the system and can affect the headway, train length, trip speed, or level of automation of the whole line.

An interesting postscript to this discussion of transit headways is the issue of headways on city streets and highways. Normal automobile traffic operates under headways of 1 to 3 sec, whereas buses (3.5 sec) and street cars (5 sec) can operate at only slightly higher values (*3*). These values appear to present an opportunity for tremendously improved capacity over the transit systems discussed earlier, but there are three conditions that severely limit the performance of these street systems. First, these street headways are theoretical, and the time-averaging realities of traffic lights and crossing traffic are ignored in their calculation. The lowest average headways observed in actual operations for buses and street cars are 10 and 20 sec, respectively (*3*). Second, these headways are achieved at the lower speeds of city streets. Because vehicle stopping distances increase roughly with the square of the vehicle's speed, headways increase correspondingly for any transit mode, just by the laws of physics. Third and, perhaps most important, the level of safety on city streets is inherently lower than on fail-safe transit systems.

This safety issue is evident from an empirical comparison of the number of accidents and overall per-passenger safety records of street traffic, compared with fixed guideway transit systems. There is also a clearly identifiable engineering rationale behind this observation. The design of ATP-controlled fixed guideway transit systems has historically involved the use of a no-collision, brick-wall safety policy. That is, the automatic train control (ATC) systems are designed so that every train will maintain sufficient space between itself and its lead train so that it can stop safely without hitting the lead train (no-collision) if the lead train is assumed to make an instantaneous (brick-wall) stop at any time. The brick-wall assumption is a virtual impossibility, but because it is so conservative, it creates an extremely safe design environment. Drivers of street vehicles (including buses and streetcars) seldom enforce such conservative safety measures under peak capacity conditions.

Platform Safety

A number of intrusion detection and platform safety devices have been designed to detect or protect people on the track in platform areas. Vancouver has red panels between the rails that are electronically tuned to differentiate between the weight of a person and other, smaller objects on the tracks. Many systems have emergency power cut-off switches ("blue light" stations) that can be activated by patrons on the platform, but these switches have become targets for vandals in some systems. Safe refuge areas have also been built under platform edges. These techniques provide an added degree of safety but can never preclude an untimely fall, a suicide, or a blind person who mistakes a gap between cars for a door entrance. These unfortunate events will still happen. Furthermore, although vehicle alarm precautions are taken to prevent train doors from closing and locking on people or clothing, circumstances still occur which lead to the dragging, or at least terrifying, of patrons who are caught by the doors.

In contrast, on fully automated building elevators, though the door mechanisms are similar to those on transit systems, the magnitude of these safety problems are dramatically reduced. This is because two sets of elevator doors are used: those in the elevator car and those on each floor. On transit systems it is only through the highly accurate station stopping of automated systems that the elevator safety equivalent of double doors can be utilized. The use of station platform doors in Lille, France, for example, has been a major factor in achieving a perfect record of no injuries or deaths in the first six years of operation, even though a projection of such events from the Paris RATP system on a per passenger basis would predict several incidents each year in Lille.

Furthermore, the risk inherent to elevators of being trapped in the cabin in an emergency or power outage does not usually exist in ALT applications because of emergency walkways and egress through the platform edge walls of stations. These walls can be designed as a continuous row of doors, all readily openable from the vehicle or track side, as in Lille.

While safety is the primary reason for platform doors, or at a minimum, gates, other secondary considerations also exist:

- Liability insurance rates may be lowered by improved safety, perhaps even to the extent of paying for the capital cost of the doors;
- Platform edge safety widths may be reduced, thereby narrowing the waiting area and resulting in lower station capital cost and perhaps even lower visual intrusion;
- Large and small operational disruptions at platforms, from falling objects and nuisance blue light alarms, are minimized;
- Opportunities for vandals to generate graffiti on the outside of vehicles are reduced;
- Station heating and air conditioning cost savings during operation can be significant;
- Passengers can be protected from various guideway annoyances and hazards (steel wheel–rail noise, train airblast from tunnels, smoke in emergency fire situations, etc.); and
- Opportunities are increased for skip-stop or express operation through stations at higher speeds than are possible with open platforms.

Ride Comfort

Just as the automobile driving habits of some people can induce stress or car sickness in their passengers, so too do transit properties have problems in achieving reliable quality driving from operators on driven systems. The irregular driving patterns of train operators can tire or cause discomfort among passengers.

In contrast, automated systems are designed to have reliably steady acceleration and deceleration patterns that are often performed at very brisk rates. This automation can instill in the passengers a sense of efficiency, reliability, and confidence in the system. In fact, in this high-tech space and computer age, the reliable, crisp operation of automatic train operation ALT offers a rare positive image for public transit.

Schedule Modification

Although schedule planners try to anticipate the public's demand on a transit system, there will always be days or hours of unexpectedly high or low demand. When trains are driven or attended, the addition of one train may be impossible because of crew availability. Similarly, the deletion of unanticipated surplus trains is usually not even considered because the marginal cost savings is so small. There is an unavoidable cost for the crew that has already reported or, at least, is scheduled for work.

These are not problems in most fully automated systems. The calling of extra trains into service or deletion of trains from scheduled service is achieved via simple keyboard inputs at Central Control. After an addition or deletion, scheduled train dispatches can be routinely adjusted to distribute the new number of trains uniformly throughout the system or to group several trains into a bunch at shorter headways to run them through the system as an intentional "pulse" of higher capacity.

Off-Peak Service

Similarly, in midday and late night hours, the frequency of service of manual systems is limited primarily by labor scheduling and costs, not vehicles. In contrast, on automated systems the frequency of service can be easily increased with only small marginal cost impacts. The resulting convenience for passengers can attract greater off-peak patronage, lower the security risk of the station wait to users, and generally improve the overall usefulness of the system in the eyes of the public.

Failure Management

Delays that cause trains to fall behind schedule are typically addressed first by the use of progressively more severe schedule maintenance techniques. These include:

- Shortening station dwells;
- Using higher, but still safe, speeds (if available) between stations;
- Slipping the schedule of other trains; and
- Skipping selected stops.

In these schedule maintenance techniques, passengers continue to use the train because the delay was caused by an external problem or a failure that was not related to safety on their train. The train can be replaced at the end of the line, if necessary. All of these techniques can be included in the train supervision of any driven, attended, or automated system. They can usually be performed more quickly in an ALT system, however, because most of the central control and automation tools needed to implement the techniques are inherent to the ALT system. This is another example of the compounding of benefits from automation, as discussed previously.

When schedule maintenance techniques are insufficient to deal with an operating delay, or when a safety risk is involved, the failure management function must take over. The intent of failure management is first to get the passengers to safety (usually at stations) and then to remove the problem train from the main line as quickly as is practical so that service may be restored. Here again, there is a hierarchy of increasingly severe techniques, typically including

- Skipping some or all stops (after unloading passengers);
- Being pushed or pulled by another train;
- Intervention by emergency repair crew; and
- Being towed away by an independently powered maintenance vehicle.

ALT systems offer the opportunity for the first two of these techniques to be implemented more quickly than in either driven or attended systems, which require formal communications, perhaps the opening and initiation of manual control panels, and cab changes. Furthermore, as mentioned in the section on compounding of benefits from automation, ALT vehicles are designed for fewer disabling failures.

Efficient Administration

As transit systems are required to be more cost effective, questions of reliability improvements, maintenance planning, and general administration efficiency become more pressing. The success of each of these can be heavily influenced by the availability of the right data from a management information system (MIS). The MIS in turn is only as good as the freshness and quality of its source data. Because the communication infrastructure usually provided with AGT systems is typically quite extensive, the addition of specific record keeping and information processing functions within the MIS can often be implemented simply by adding software or minimal new hardware interfaces. Although a similar data-gathering system could be provided for driven or attended systems, such a modification might mean added capital cost. Those costs might be small, but the changes that incur them are likely to be viewed as "niceties" rather than "necessities," so such additions are therefore thought to be incompatible with the original rationale for selecting technologically simpler systems. Thus sophisticated communications are frequently not provided on simpler systems, and as a result, record keeping in AGT systems becomes an example of compounding of benefits from automation.

COST POSTSCRIPTS

The technical comparisons just made are one part of the larger question of how to select a transit system for a city. That larger issue is dominated by cost concerns. A brief perspective discussion on costs is provided in Appendix C.

CONCLUSION

The comparisons presented in Table 1 demonstrate that fully automated ALT systems have several significant performance, safety, and dependability advantages over both driven and attended transit systems. ALT systems represent a technically preferable alternative to more conventional driven and

attended transit systems for those cases in which medium- to high-capacity transit that offers high-quality service (in terms of travel times and service frequency) is desired.

APPENDIX A: TRAIN CONTROL TERMINOLOGY

Train control is classically divided into three major functional groups (*4*):

- *Train Protection* The prevention of collisions and derailments.
- *Train Operation* The control of train movements between, and stops at, stations.
- *Train Supervision* The direction of train movements in relation to each other, route alternatives, a schedule, or any combination of those factors.

The typical functions performed within each group are as follows. Additional, related functions that may be performed by the transit system's associated communications and supervisory control and data acquisition (SCADA) networks are also presented.

- Train Protection—Tracking:
  T.1. Location,
  T.2. Direction, and
  T.3. Speed;
- Train Protection:
  P.1. Separation enforcement,
  P.2. Merge conflict resolution,
  P.3. Overspeed protection—(a) civil and (b) slow order,
  P.4. Guideway intrusion detection,
  P.5. Door operation/train motion interlocks,
  P.6. Platform/vehicle door position interlocks, and
  P.7. Switch lock protection;
- Train Operation:
  O.1. Speed regulation—(a) profile control, (b) cruise, and (c) separation,
  O.2. Station stopping,
  O.3. Door open control—(a) platform side and (b) location/zero speed,
  O.4. Dwell control,
  O.5. Routing (diverge control), and
  O.6. Alarm response—(a) immediate and (b) delayed;
- Train Supervision:
  S.1. Route assignment,
  S.2. Schedule dispatching,
  S.3. Schedule modifications,
  S.4. Schedule maintenance,
  S.5. Failure management,
  S.6. Fault detection, and
  S.7. Record keeping;
- Communications (Audio and Visual):
  C.1. Fire/police emergency phones,
  C.2. Passenger information,
  C.3. Security—(a) on board and (b) at stations, and
  C.4. Operations and maintenance;
- SCADA:
  D.1. Traction power monitor and control,
  D.2. Fare collection equipment monitor,
  D.3. Building intrusion detection,
  D.4. Tunnel ventilation control,
  D.5. Fire alarms, and
  D.6. Seismic and tunnel gas monitor.

The increasing use of automation in performing the train control functions has led to the common use of the following abbreviations:

- ATC: Automatic Train Control; and its subsets:
- ATP: Automatic Train Protection,
- ATO: Automatic Train Operation, and
- ATS: Automatic Train Supervision.

All train control automation is not the same. Different combinations of functions may be automated, and the levels of performance of the automation can be markedly different, usually depending on the technical sophistication. To automate safety-related functions, additional requirements for rigorous fail-safe design are added.

Given these three variations on the more than 20 ATC functions listed previously and the variations in design approaches taken among various manufacturers, it is not surprising that hardly any two transit systems have been automated in exactly the same way. Furthermore, recent momentum in Los Angeles and Houston, for example, indicates that individual cities may continue to design their own nonstandard systems. Los Angeles is moving toward the separate procurement of an LRT-compatible vehicle and a fully automated ATC, whereas Houston seems to favor a conventional turnkey fully automated system that has a manual operating mode.

In spite of these complexities, train control automation can be classified into three categories, ranging from little or no automation to the full extent of AGT. These are the three levels discussed in the paper: driven, attended, and fully automated.

APPENDIX B: TRANSIT TERMINOLOGY

One technical characteristic of transit systems has been explored in this paper: the level of automation in the operation of the trains. That categorization of transit systems differs somewhat from the more popular classifications (*5*) by

- hardware (e.g., light rail = modern streetcars set in a variety of rights-of-way),
- rights-of-way (mixed traffic, grade separated, etc.),
- technology (rubber tire, steel wheel, etc.), or
- service (regular, commuter, etc.).

Therefore a discussion of automation level with respect to current systems, practices, and terminology may be useful as a touchstone.

Typically, manual systems (both driven and attended) have been procured by using separate contracts for each major subsystem (vehicles, ATC, traction power, etc.). These systems generally fall into two categories, based loosely on carrying capacity and vehicle design: light rail transit (LRT) and heavy rail transit (HRT). Heavy rail is also sometimes referred to by the more generically proper term "conventional

rapid transit" (CRT) to allow for alternate technologies (e.g., rubber tires).

In contrast, AGT systems (fully automated) are built under single contracts, with the system supplier providing all transit-related hardware. Sometimes, in "turnkey" contracts, even the guideway and station facilities are provided by the system supplier. This simplifies the contractual interface for the transit authority and puts the facilities design and construction risk into the hands of the system supplier instead.

Subcategories within the general AGT umbrella were defined by the U.S. Congress in 1975 (*6*) as shuttle loop transit (SLT), group rapid transit (GRT), and personal rapid transit (PRT). Unfortunately, however, that report did not allow for a fourth subcategory of AGT, which is referred to here as automated line haul transit (ALT). It is characterized by:

- line haul configurations,
- full automation (no drivers or attendants required on board), and
- high performance (higher speed than other AGT, lower headways than conventional transit, and medium to high capacity).

ALT includes the operating systems in Lille and Vancouver and the designs selected for Los Angeles, Taipei, Lyon, Bordeaux, Toulouse, and Strasbourg. In contrast, "people movers" in airports, activity centers, and amusement parks are usually better classified as SLTs or GRTs. One reason is their lower performance levels. Other considerations frequently include a lack of the characteristics required for urban applications (e.g., ease or speed of switching) or private ownership that excuses them from public requirements (e.g., fire or life safety standards). Anomalies and different opinions abound, however, in attempts to classify specific systems rigorously. Some experts refer to Vancouver's fully automated system as an LRT rather than an AGT. The new Century freeway system will probably use LRT vehicles procured under contracts separate from those for the ATC system, but will be a fully automatic system. UTDC's Intermediate Capacity Transit System (ICTS) has been installed as both manual ("attended" in Scarborough) and fully automated (ALT in Vancouver, SLT in Detroit) systems.

This paper sidesteps these differences in global definitions by concentrating on the one technical characteristic discussed earlier: the level of automatic train control. The determination of whether a system is driven, attended, or fully automated (as defined herein) is easily made, and the implications for performance, safety, and dependability discussed satisfactorily.

APPENDIX C: COST GENERALIZATIONS

ROW Cost

To physically build a rapid transit system, a city must have two prime resources, right-of-way (ROW) and funds. Ultimately, it is ROW, including real estate and civil structures, that sets an upper limit on the level of performance of the system. A truly grade-separated system adds all-new transportation capacity to a city. Any compromise on full grade separation not only limits the speed and capacity of the new system to something less than their fullest potentials but also places a new restriction on the capacity of the existing transportation infrastructure because of shared traffic lanes, prioritized signals, grade crossings, and so on.

Poor ROW can be improved by the funding of grade crossing eliminations, elevated structures, tunnels, and similar projects. These separate the transit system from the restrictions of street traffic but invariably translate into a need for more funds. Thus, early in the rapid transit planning process, each city faces a tradeoff between the quality of the transit system's performance and ROW and civil structure costs.

This tradeoff is the most significant issue in scoping the characteristics of a transit system. However, funding and ROW resources are political and urban issues. Although the tradeoffs between them usually result in restraints on the transit system, these restraints should not be confused with the innate technical limitations of various hardware systems. Separate understandings of political and urban concerns and technical issues are needed to properly select a transit system for a city.

For example, existing city streets offer the advantage of no ROW cost for the transit system but result in bus and streetcar transit systems, which are constrained to low performance by automobile traffic. Light rail offers flexibility in selecting a low level of ROW capital cost but at the expense of performance limits. The weakest link of a system, as mentioned in the discussion of shorter headway, is a grade crossing or a mixed traffic area. If these weak links are not eliminated because of cost constraints, the transit hardware is prevented from performing up to its full potential on other parts of the line. The extensive grade crossing–elimination program on the northeast rail corridor is an example of the need for increased safety and reduction in operating delays and personal property damage on an operating railroad system. The cost of those reconstructions is a testament to the cost premium to be paid when such modifications are not made as part of the original design.

It is only on fully grade-separated ROWs (elevated, tunneled, or fenced at grade without street crossings) that the maximum performance capabilities of all transit systems are unhindered. Unfortunately, the cost of achieving that grade-separation can vary significantly from city to city and even corridor to corridor. Whether the city has the ROW and financial resources available to achieve separation is a site-specific political and urban tradeoff. To divorce the site-specific tradeoffs from an understanding of the technical issues, fully grade-separated ROW has been the common ground assumed in this paper.

Within this framework of fully grade-separated ROWs, some generalizations about ROW costs are made. Automated systems can be used to allow shorter stations, smaller diameter tunnels, narrower guideways, and tighter turning alignments than are possible on equal-capacity driven systems and some attended systems, as discussed in the section on shorter headways.

System Capital Costs

In a subsystem-by-subsystem comparison, fully automated transit systems are expected to have a marginally higher capital cost than attended systems. For example, the 20-mile

Norwalk–El Segundo rail line of the Los Angeles County Transportation Commission is completely at grade and will be fully automated (7): "The additional cost of automation for the . . . line is $23 million, bringing the total to be spent on the rail project to $368 million." This 6.25 percent of the system cost would, of course, be a much lower percentage if the system had been elevated or tunneled (or both). Similarly, attended systems can be expected to have a higher cost than driven ones.

Primary Operating and Maintenance (O&M) Cost Issue

The most significant cost advantage of fully automated systems lies in the productivity of labor. When a crew member is required on each driven and attended train, a corresponding total of four or five employees are needed on payroll to allow for multiple shifts, vacations, lost time, hourly variations in the number of trains in service, supervision, and administration.

In contrast, automated systems eliminate the requirement for on-board crew and instead allow flexibility in selecting an employee on-board policy. This policy can be tailored to the passenger assistance, security, and ticket checking needs of the locale and hours of the day. Thus the staffing levels of attended systems represent a worst case, or upper limit, of the staffing required by an equivalent fully automated system in the same application. Furthermore, the on-board operating personnel required in manual systems are more technically trained (and hence may represent a higher salary level) than the fare collection, security, and information employees needed on a fully automated system.

In Lille, for example, although 12 employees are required for maintenance of the ATC system and 26 for ticket control, passenger information, and first-line fare collection equipment repairs, it is estimated that 102 additional employees would have been needed over the 1987 total staff of 185 if the system had been driven or attended. In terms of productivity, that would have changed the 146,000 passengers per year per employee to 95,000.

Secondary O&M Costs

Secondary O&M cost savings from fully automated systems have been identified, as follows:

- Shorter headways can mean a general reduction in ROW requirements, such as shorter stations, smaller tunnels and guideways, or tighter turning alignments. A portion of these changes translate into lower O&M costs.
- Platform safety can reduce insurance premiums, allow narrower platforms, and possibly reduce blue light and trackwork subsystems costs.
- Schedule modifications can save operating costs by easily tailoring service to demand without the restrictions of crew scheduling.
- Efficient administration can increase employee productivity.
- Off-peak level-of-service increases can induce additional patronage, thereby increasing revenues.

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