AUTOMATIC GUIDED VEHICLES

Automated guided (or guideway) transit is an advanced transportation system in which automated driverless vehicles operate on fixed guideways in exclusive rights-of-way (1). These differ from other forms of transit in that no operators are required on the vehicles. This feature makes it possible to provide a high level of service throughout the day either through more frequent service or service in direct response to passenger requests.

Initial work on this transit technology probably began in the 1950s when General Motors was doing in-house research on automated highways and other companies were developing ideas on systems using driverless vehicles on separate guideways. The US government began supporting automated transit systems by providing a grant to Westinghouse in the early 1960s to assist in constructing a test facility in Pittsburgh for a system known as Skybus or Transit Expressway. Significant impetus for developing automated guided transit (AGT) systems in the United States was provided in 1966 by the Reuss-Tydings Amendments to the Urban Mass Transportation Act of 1964. The amendments required that a project be undertaken to study and prepare a program of research, development, and demonstration of new systems of urban transportation. In the 1960s and 1970s extensive research studies were undertaken on AGT systems (2). Several manufacturers developed prototypes and early applications included installations at the Tampa and Dallas–Fort Worth International Airports and in Morgantown, West Virginia, on the campus of West Virginia University. Research and development was also undertaken in Canada, Europe, and Japan.

Since the late 1960s, automated guided transit has been used in a variety of applications including airports, amusement parks, zoos, hospitals, shopping centers, resorts, downtowns, and other major activity centers. Currently, there are almost 100 installations of various types and configurations operating throughout the world, and many more are under construction or are being planned (3–9).

AGT systems vary greatly and differ in the degree of technical sophistication, service attributes, and vehicle operations. There are four basic categories of AGT systems:

1. Shuttle-loop transit (SLT) systems are the simplest type of AGT in which vehicles move along fixed paths with few or no switches. The vehicles in a simple shuttle system move back and forth on a single guideway, the horizontal equivalent of an elevator. Vehicles in a loop system move around a closed path and stop at any number of stations. In both shuttle and loop systems, the vehicles vary in size and travel singly or coupled together in trains. SLT are often configured to provide passenger service in a confined area, such as an airport, amusement park, or downtown. This class of AGT is often called automated people movers (APM), people mover systems (PMS), or downtown people movers (DPM). Examples include Orlando and Tampa International Airports, or the Detroit DPM.
2. Group rapid transit (GRT) systems involve operating vehicles over a network of connecting lines and/or loops and more extensive use of switching. Three examples are the Airport Train system at the Dallas–Fort Worth International Airport, the Morgantown system on the West Virginia University campus, and the Miami Metromover that operates in downtown Miami, Florida. GRT systems require sophisticated technologies and extensive automatic train supervision software.
3. Personal rapid transit (PRT) is a concept similar to GRT except that very small vehicles provide nonstop personal service between off-line stations. This class generated considerable interest in the professional and academic communities during the early seventies, and networks were envisioned as large systems for citywide service or small systems for activity centers. No PRT system has been built, and the original concepts have evolved to more conventional shuttle or loop-type people mover systems. However, interest has resurfaced and PRT systems are being considered in Chicago area studies, Seattle, and Sweden.
4. Line haul systems provide service similar to light rail transit (LRT) or rail rapid transit but use automated vehicles. This class has been called minimetro, auto-

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> mated rapid transit, and advanced light rail transit. The VAL system in Lille, France, the Vancouver Skytrain, and the London Docklands system are examples of line haul AGTs.

In contrast to bus and rail transit systems in which generic designs or vehicles are supplied by a variety of manufacturers, each AGT system is a proprietary design. An AGT system must be procured from the manufacturer who owns the design. The guideways and stations (i.e., the civil infrastructure) can be procured separately but must be specifically constructed to interface with the proprietary system. The result is that vehicles of one manufacturer cannot easily be adapted to a guideway constructed for the vehicles of another manufacturer. In addition, because each AGT system/technology is a proprietary design, there is a very wide range of available features.

In Japan, steps have been taken to standardize vehicles and design, but in North America the work on standardization has concentrated on definitions, measurements, and safety aspects.

The AGT industry has been constantly changing: manufacturers leave, new ones enter, and companies merge. Although there are various systems available, there are four basic components—the vehicles, the guideway, the stations, and the control system.

Vehicles

Automated guided vehicles (AGV) come in a variety of designs such as monorail, rubber-tired, steel-wheeled, magnetically levitated, suspended, or cable drawn. The original concepts were based on small vehicles, but today the vehicles are typically about the size of an urban transit bus. On many systems vehicles are linked to form trains. For many applications, the vehicles are designed to carry standing passengers and few seats are provided because it is typically a short ride. Operating speeds range from 20 to 70 km/h and short headways are common, although higher speeds and longer headways are used on line-haul applications. Figure 1 shows examples of two automated guided vehicle designs—a rubber-tired vehicle, and a monorail design. On some installations, there are capabilities for full automation, but the provider has chosen to have an operator on board. For example, at some amusement parks and zoos, the operator provides a personal welcome or identifies specific attractions or animals to the passengers.

Guideway

Automated guided transit systems require an exclusive, dedicated guideway primarily because of the automated operation. The guideway structure can be constructed below grade in tunnels, at grade, or in elevated alignment. Specific design details depend on the system, but generally the guideway consists of steel and reinforced-concrete sections.

The alignment for each system is unique to accommodate service requirements. Most systems in operation today are a shuttle, pinched or reverse turnback loop, or loop configuration. The simplest layout is a single guideway in which a bidirectional vehicle shuttles back and forth between two stations. Adding a parallel guideway doubles the capacity, reduces the headway, and improves system availability. The reverse turnback or pinched-loop layout allows vehicles to follow one another with relatively short headways. This layout is similar to most rail rapid systems, and loops or switches are incorporated at the ends of the line. A third variation is the single, closed loop where no switches are required, and vehicles travel in a clockwise or counterclockwise direction around the loop. A second loop can be added on which vehicles operate in the opposite direction. This increases capacity and provides better service to passengers. A further variation is overlapping routes on multiple loops.

Two additional elements of a system often associated with the guideway are power collection and switching. Power is usually collected by a power rail on the guideway and collectors on the vehicle. Switching, if required, is usually by moveable beams or sections on the guideway, but may be done with vehicle-mounted mechanisms.

Stations

Stations for passenger access are located along the guideway and can be on-line or off-line depending on the system operations. An on-line station is located on the main line, and an off-line station is removed from the main line where loading/unloading vehicles does not impede mainline flow. The off-line station is a common feature in PRT system concepts. Today, most systems use on-line stations and passengers board from station platforms level with the floors of the vehicles. The platforms may or may not be separated from the guideway by a barrier wall whose doors coordinate to operate with the doors of a stopped vehicle. The design of a specific station depends on the system operational requirements and forecasted passenger demand.

Control System

To have driveless vehicles, an automated train control (ATC) system is required to enforce train safety, automatically control train movement, and direct train operations. In general, the level of sophistication of the control and communications systems increases as the operational capabilities of the system grows.

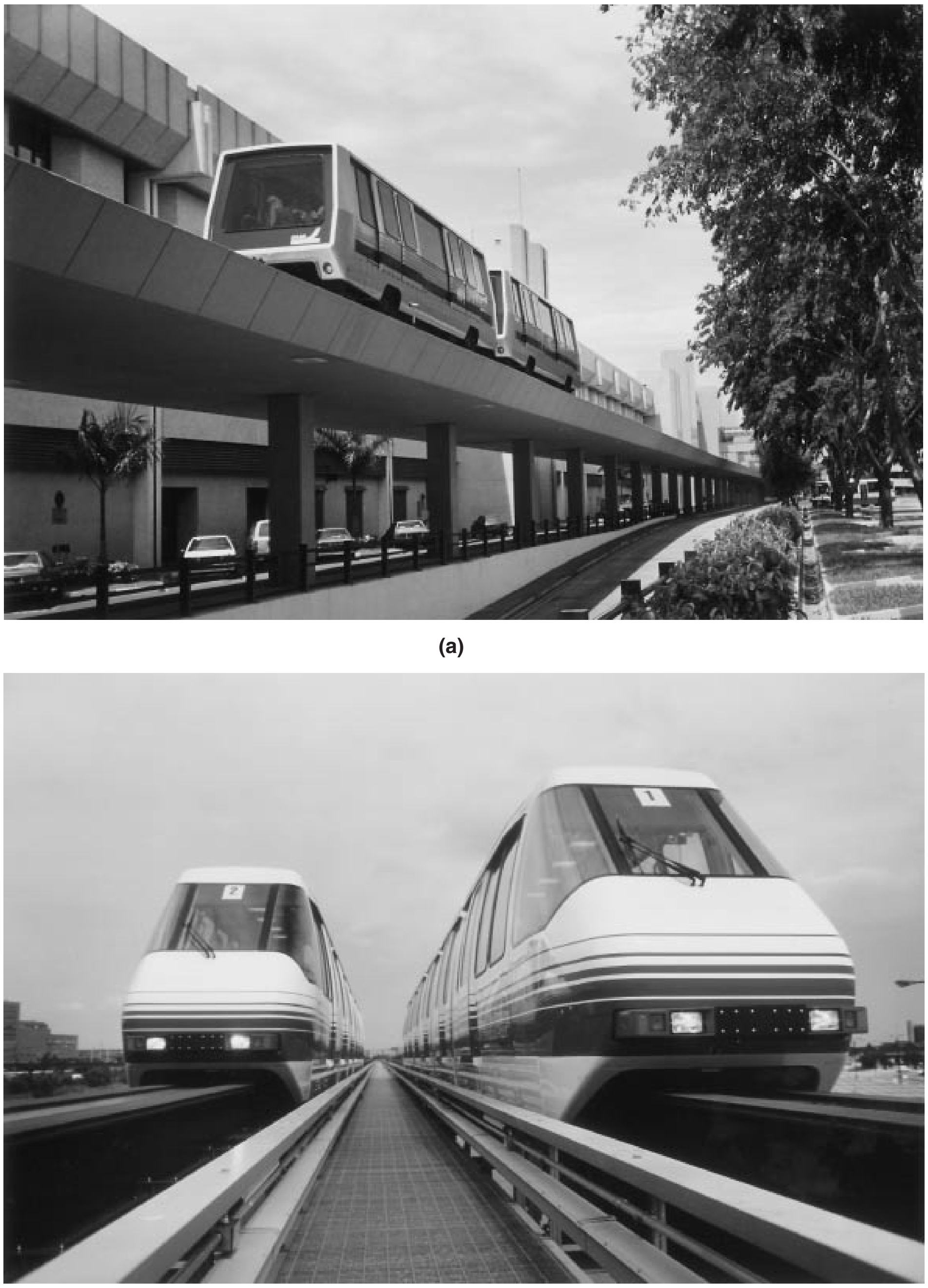
AUTOMATIC TRAIN CONTROL

The functions of automated train control (ATC) are distributed among three subsystems: train protection, train operation, and train supervision.

Automatic train protection (ATP) maintains fail-safe protection against collisions, excessive speed, and other hazardous conditions by knowing approximately where vehicles are located, how far apart they are, how fast they are traveling, how fast they are allowed to travel, and the status of all switches.

Automatic train operation (ATO) controls vehicle speed, programmed stops, door opening and closing, and other functions which would otherwise be controlled by the train operator.

Automatic train supervision (ATS) monitors all vehicles in the system, adjusts the performance of individual vehicles to maintain schedules, and generally performs those functions that would be controlled by a train dispatcher in a traditional nonautomated rail system.



(a)

(b)

Figure 1. (a) Automated guided vehicles operating at Changi International Airport, Singapore; rubber-tired vehicles, CX-100 design. (b) Automated guided vehicles operating at Newark International Airport, Newark, NJ; monorail system. Photo credit: ADtranz.

Fully automated guided vehicle systems require complete ATP, ATO, and ATS capabilities. Conventional railroads often incorporate many ATC features, but they are usually not fully automated. The Washington Metro, the rail rapid transit in the Washington, DC, region, is capable of fully automated operation; however, by design door control remains under the direct control of the train operator. For a typical signalized railroad, only train separation and switch positioning are controlled by ATP.

Automatic Train Protection

Automatic train protection (ATP) is the heart of automatic train control because this system checks that all functions involving the movement of vehicles are done safely. It should never be possible for any ATO or ATS functions to overrule an ATP decision. Conversely the ATP must be able to override any ATO or ATS command. The automated guided vehicle community has agreed upon the following ATP functions which are required by ASCE 21-96, Automated People Mover Standards—Part 1 (10).

Presence Detection. Presence detection determines the location of every vehicle in the system. Traditionally, railroads have accomplished this by dividing the track into blocks or electrically isolated sections. A signal is sent from one end of the block to the other. The presence of a train shunts the circuit, removes the voltage and causes a relay to drop. Dc track blocks are insulated, whereas ac circuits use inductive coils to achieve electrical isolation. Modern systems use variations of this traditional method. Presence detection must be continuous or must repeat at a frequent cyclic rate so that loss of signal is detected in sufficient time not to compromise safety. More than one train should never be in any safety block. To prevent undetected uncoupling of trains within a block, protection is provided which detects any uncoupling and automatically stops all cars in the train.

Separation Assurance. Separation assurance, also known as safe headway control, protects against rear end collisions by maintaining a zone behind each train that provides sufficient stopping distance for the following train. Where AGT systems permit automated operation of trains in opposing directions on the same track, separation assurance using stopping distances for both trains must be considered to prevent head-on collisions. It is accepted practice to use what is called brick-wall stop criteria. This assumes that the lead train can stop instantaneously. Because early ATP systems had no way of knowing the speed of the vehicle ahead or its precise location within a block, it was necessary to assume that the lead vehicle was stopped at the block entrance. With modern systems, it is possible to know the actual speed of the train ahead, and it has been argued that the brick-wall stop penalizes system performance. Stopping distance calculations must use worst-case characteristics, including the possibility of runaway acceleration, minimum braking capability, maximum cumulative reaction times, maximum attainable overspeed, the effects of downhill grades, maximum passenger loadings, minimum adhesion or traction, and maximum anticipated tailwinds.

The minimum possible headway for any transit system is equal to the safe separation plus the train length divided by the vehicle speed. It is not practical to actually run an AGT system at this minimum headway. For example, if train location is determined by blocks, this uncertainty in train location must be taken into account and further increases the headway. Headway has key economic impacts because line capacity or throughput in vehicles per hour is inversely related to headway. Advances in automated guided vehicle command and control systems are geared to take advantage of more accurate information on train position and velocity to reduce headway and make it possible to send more trains per hour down a given guideway. If the trains stop at stations on-line, headway reduction is physically limited by the dwell time in the station and the time lost in accelerating and braking. On-line stations typically add 30 s to the required headway. Although low-speed (20 km/h to 25 km/h) systems achieve operating headways of 60 s, 90 s to 120 s are more common.

Overtravel Protection. In addition to protection against train collisions, it is also necessary to protect against running off the end of the guideway at terminals. Where there is insufficient guideway in the back of the terminal station to assure stopping under worst-case conditions, supplemental overtravel protection, such as a buffer, is required. In general, it is recommended that buffers be provided as a backup even when adequate stopping distance is available.

Passenger Safety. Several ATP functions are related to station stopping and passenger boarding. Door interlocks require four conditions before the doors of a vehicle may be opened. The train must be aligned to provide at least 82 cm clear opening within the boarding zone, zero speed must be detected, propulsion power must be removed from the motors, and the train must be positively constrained against motion by setting brakes or other means. Because of the practical limitations of speed detection equipment, zero speed is assumed to exist when the speed has been less than 0.3 m/s for at least one second. Protections also exist against unscheduled opening of doors while the vehicle is in motion. Should any door open at any time while the vehicle is in motion, the vehicle is automatically braked to a stop. Unintentional motion detection is also provided to initiate emergency braking any time that a vehicle is detected to be moving without permission or against the permitted travel direction. In addition, direction reversal interlocks prevent reversal of propulsion thrust unless a zero speed is registered.

Vehicle Overspeed. At all times ATP must know both the speed at which the vehicle is traveling and the maximum safe speed for its location. This maximum safe speed may be set by civil design elements, such as the guideway curve radius or the guideway geometry entering a terminal area, or it may be the result of track and traffic conditions, such as approaching another vehicle or an unlocked switch. The ATP must know this safe speed and compare it to the actual speed of the vehicle. If the actual speed of the vehicle exceeds the safe speed, overspeed protection equipment must immediately command an ATP-supervised braking response. To guard against a runaway motor, propulsion power must also be disconnected. Emergency braking is irrevocable in that once it is initiated it remains activated until the train comes to a complete stop. If the ATP determines that conditions remain unsafe, the emergency braking remains in force regardless of any reset signals or actions.

Safety Assurance. Automatic train protection is critical and should be designed in accordance with fail-safe principles. The AGT industry defines fail-safe as a characteristic of a system or its elements whereby any failure or malfunction affecting safety causes the system to revert to a state that is known to be safe. AGT design has followed traditional railroad safety practices, but the entry of aerospace and aircraft firms into the business along with the development of software-based control systems has caused significant evolutionary changes in these traditional practices.

In the railroad industry, ATP systems were traditionally designed with discrete mechanical and electrical components. The effect of every relevant failure mode on system operation was analyzed and documented in a comprehensive failure mode and effects analysis (FMEA) in which the part was assumed to fail and its consequences determined. Boolean algebra and truth tables were used to analyze all possible combinations of relay states. In all cases, the results of the failure had to result in a state known to be safe. Usually this meant the vehicle was braked to a stop. Over the years, the industry developed a list of failures which occurred so infrequently that they did not have to be considered in the FMEA. For example, it could be assumed that vital relay contacts did not weld shut.

In the early years of AGT development, aerospace firms entered the business and brought with them the redundancy techniques common in that industry. These redundancy techniques were accepted with the critical proviso that redundant system outputs must be compared and both must agree. If they do not agree, the system must revert to a known safe state. This design philosophy has become known as checked-redundancy.

Automatic Train Operation

Automatic train operation (ATO) provides the functions that truly define an automated guideway vehicle. ATO replaces the train operator and permits fully automated operation. ATO controls starting and stopping, and regulates train speed, keeping acceleration within acceptable passenger comfort limits and maintaining speed below the overspeed limits imposed by the ATP. When the train approaches a station, the ATO executes a programmed station stop, automatically opens the doors subject to the ATP interlocks, and when commanded by the ATS system, shuts the doors and releases the train from the station.

Propulsion and Braking Control. Automated transit vehicles commonly use either dc or three-phase ac wayside power. Where three-phase ac power is provided, SCR control of separately excited dc motors is commonly used for propulsion. Dc wayside power is usually combined either with chopper-controlled dc motors or with inverter-controlled ac motors. Electric braking using either resistors or power regeneration back into the system is commonly combined with friction braking for normal starting and stopping of the train. Emergency braking usually relies solely on friction brakes. The ATO functions of speed regulation, acceleration, and braking are typically provided by microprocessor-based controllers. Thyristor controllers regulate armature and field voltage. Chopper-controlled dc motors are usually controlled by pulse-width modulation which varies the portion of the cycle in which current is allowed to flow. Frequency modulation is generally not used because the electromagnetic radiation interferes with signaling systems. Special load-weigh circuits may be used which increase the motor current as a function of the passenger load. For ac motors, voltage, frequency, and slip are controlled. Because frequency must be allowed to vary with speed, ac motors run through the entire frequency range during acceleration and braking, making electromagnetic interference with signaling a major concern.

Degrade Mode Operation. In addition to the normal ATO mode, some AGVs offer degraded modes in which the vehicle is automatically operated at reduced performance. This may be because of a propulsion or braking failure or because weather conditions, such as ice and snow, make such operation prudent. It is essential that all vehicles can be manually operated by a driver. Such operation is necessary to recover from failure situations, to tow disabled vehicles, and during maintenance activities. Because the vehicles are not designed for normal manual operation and because manual operation is often not controlled by ATP, most AGT accidents occur when vehicles are manually driven. The most common occurrence is running a switch or overrunning the end of the guideway. Special precautions are necessary in manual mode, and most limit the speed in this mode to not more than 25 km/h.

Automated Train Supervision

Automated train supervision (ATS) runs the railroad. It takes the place of the train dispatcher in a manual system. Most AGT systems have one or more persons in central control at all times. Some of the smaller installations have operated with no on-site central control operator, and some simple shuttle systems at airports and hospitals have combined the AGT central control function with other facility management activities such as airport operations or the communications center. The ATS has three functions: to automatically regulate the operation of the AGT system, to inform the central control operator of system status and performance, and to enable the operator to adjust system performance and intervene or override the automatic operation when necessary. Automatic regulation of AGT operations include train tracking, train routing, headway management, and control of station dwell time. Figure 2 is a photograph of a typical AGT control center.

The interface with the control operator is critical. Audio and visual displays present information describing the status of the system on a real-time basis. A system operations display shows the approximate geographical representation of the guideway and the locations of relevant physical features, such as passenger stations, switches, and maintenance and storage areas. It dynamically locates and identifies all trains in the system, their direction of travel, the number of cars in a train, and the status of all switches. Where signal blocks are provided, it shows their boundaries and occupancy status. A second power schematic display provides a visual indication of the power distribution system, including the presence or absence of power in all guideway power circuits and the status of all circuit breakers.

In addition to knowing what is happening in the system, the central control operator must be able to control it. Control includes the ability to change operating modes, add and remove vehicles from service, set up and change routes, and individually command switch positions, initiate degraded and recovery operations, hold trains in stations, stop all trains, turn off system power completely, start up and terminate service, and acknowledge and process alarms.

NEW DIRECTIONS IN AUTOMATIC TRAIN CONTROL

Developments in microprocessors and software are causing rapid change in the AGT industry. Early AGVs extended traditional railroad signaling systems to achieve automatic operation. Today, the industry is moving increasingly toward wireless communications and more extensive use of software-based train control systems.

Communications-based train control (CBTC) represents the merger of modern communications with microprocessor technology to revolutionize train control. CBTC is defined as a train control system based on continuous two-way communications between trains that does not require the use of track circuits. San Francisco BART, New York City Transit, the Philadelphia SEPTA, the Long Island Rail Road, and numerous other conventional rail transit systems are testing prototypes and are actively planning or considering communica-

Figure 2. Automated guided transit system control center at Frankfurt/Main Airport, Frankfurt, Germany. Photo credit: ADtranz.

tions-based train control. CBTC uses radio communications in place of track shunting to locate trains and communicate information. Spread-spectrum techniques developed for the defense industry are being tested for their ability to improve communications reliability in the noisy transit environment.

Software is increasingly being used for vital safety in AGT systems. The major issue, familiar to anyone who has programmed software, is that it is not possible to guarantee that there are no software errors in a computer program, that is, it has been completely debugged. The economic pressures to replace costly electromechanical relays with microprocessors are overwhelming, but given this inability to completely debug software, the question is how can a safe system be designed. A number of techniques have been proposed and are now in use. *N*-Version programming uses at least two, parallel, programmed software systems performing identical functions. The software in each system is independently written by different persons or teams using different languages and tools. Outputs from the two programs are compared and if they do not agree, the system defaults to a safe state. Diversity and self-checking is an approach in which critical functions are performed in diverse ways, using different software routines, and checks are made for correspondence and logical consistency. Disagreement or inconsistency in the diverse software operations causes the system to revert to a known safe state. Numerical assurance is another technique being used with vital software. In this technique permissive decisions are represented by large unique numerical values, calculated by combining numerical values that represent each of the critical constituents of the decision. The uniqueness of the calculated values protects against software errors in any of the subroutines that contribute to the final result.

Methods for validating and verifying software safety are still being developed in the industry. In the United States, the IEEE is developing a standard to govern Safety Considerations for Software Used in Rail Transit Systems (11). In Europe, the Commission of the European Communities has a project, Certification and Assessment of Safety—Critical Application Development, that has developed a Generalized Assessment Method for planning and assessing a software intensive safety critical system (12). Much activity can be expected in this area in the years ahead.

DEVELOPMENT OF STANDARDS FOR AGT SYSTEMS

Considerable effort is underway in developing standards for AGT systems. In the United States, those active in automated guided transit systems should be aware of ASCE 21-96, Automated People Mover Standards, Part 1 (10), that covers operating requirements, safety requirements, system dependability, automatic train control, and audio and visual communications for AGT systems. Part 2, governing vehicles, propulsion, and braking is expected to be released in 1999, and a Part 3 covering electrical aspects, stations, and guideways is being drafted. Australia has a Fixed Guideway People Mover Standard, AS 3860-1991 (13). In Europe, the Germany BOStrab has developed regulations covering automated people movers which have been used in Germany and Denmark. The Japanese have also been active in AGT standards. However, although the US, European, and Australian efforts have been oriented to consistent safety and performance standards, the Japanese focus has been on defining a standard vehicle/guideway interface to permit interoperability of systems built by different manufacturers. Because of the small size of the AGT industry, standards are viewed as necessary for passenger safety, and to rationalize the procurement process and reduce costs.

FUTURE TRENDS

Over the years, automated guided transit has matured in both concepts and technology. The exotic prototypes that were originally envisioned for urban transportation with small vehicles, on-call operations, and off-line stations have gradually been replaced by systems with more conventional transit characteristics. Several of the AGT technologies have proven operating records and the interest in these systems grows. Applications for AGT in major activity centers, especially at airports, continue to expand. Exciting projects are being planned using personal rapid transit (PRT), and full automation is being incorporated on several line-haul rail rapid transit systems in Europe.

BIBLIOGRAPHY

1. B. H. Gray (ed.), *Urban Public Transportation Glossary,* Washington: Transportation Research Board, National Research Council, 1989.
2. Automated Guideway Transit-An Assessment of PRT and Other New Systems, Washington: US Congress, Office of Technology Assessment, 1975.
3. E. S. Neumann and M. V. A. Bondada (eds.), *Automated People Movers-Engineering and Management in Major Activity Centers,* New York: American Society of Civil Engineers, 1985.
4. M. V. A. Bondada, W. J. Sproule, and E. S. Neumann (eds.), *Automated People Movers II-New Links for Land Use-Automated People Mover Opportunities for Major Activity Centers,* New York: American Society of Civil Engineers, 1989.
5. T. Inouye, T. Kurokawa, and W. J. Sproule (eds.), *Automated People Movers III-Future Prospects for APMs,* Tokyo, Japan: Japan Society of Civil Engineers, 1991.
6. W. J. Sproule, E. S. Neumann, and M. V. A. Bondada (eds.), *Automated People Movers IV-Enhancing Values in Major Activity Centers,* New York: American Society of Civil Engineers, 1993.
7. *APMs: Towards the 21st Century, 5th Int. Conf. Autom. People Movers-Century,* Paris, France: Association Francaise des Sciences et Technologies de l'Information et des Systemes, 1996.
8. W. J. Sproule, E. S. Neumann, and S. W. Lynch (eds.), *Automated People Movers VI-Creative Access for Major Activity Centers,* Reston, VA: American Society of Civil Engineers, 1997.
9. T. J. McGean, *Urban Transportation Technology,* Lexington, MA: Lexington Books, 1976.
10. *Automated People Mover Standards, Part 1,* ASCE 21-96, New York: American Society of Civil Engineers, 1997.
11. T. J. McGean, Developing IEEE rail transit vehicle standards, *Proc. 1998 ASME/IEEE Joint Railroad Conf.,* New York: American Society of Mechanical Engineers, 1998.
12. *Generalized Assessment Method,* P 9032 CASCADE, Part 1: Rules, Part 2: Guidelines, Part 3: Examples. CAS/LR/WP2.T3 SM/D2.3.1, Croydon, United Kingdom: Lloyd's Register, January 1997.
13. *Fixed Guideway People Movers, Australia Standard,* AS 3860-1991, North Sydney, Australia: Standards Australia, 1991.

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