Cable-Propelled People Movers in Urban Environments

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Cable-propelled people mover systems have been studied and implemented in a variety of urban applications, including airports, downtowns, feeders to regional transit, feeders to remote parking, internal circulation in large developments, and leisure facilities. A family of technologies exists that offers a wide range of performance and design characteristics. The features and application potential of the various technologies, as well as experience to date, are discussed, and a classification system that groups technologies by service type (reversible, continuous, and pulsed), capacity of transport unit, and method of support is presented. Alignment features, velocity, gradability, capacity, and costs are compared. Specific urban sites are referenced.

Previous research indicates that installation of automated people movers (APMs) in development projects has represented about 7 percent of the total project costs, which is close to but lower than typical elevator costs for developments (*1*). Ideally, the costs should be sufficiently low that little or no federal assistance would be necessary for implementation. Cable-powered APMs have been identified as an "appropriate technology" because they have potential for requiring less expensive vehicles, less sophisticated command and control systems, and less expensive guideways. Those types of systems in widespread use in ski resorts also use off-the-shelf hardware and incur lower engineering and administrative costs. Performance of cable systems can equal or be superior to more sophisticated technologies over short travel distances on relatively simple networks (two or three station shuttles). For example, continuous cable systems can offer vehicle headways as low as 8 or 9 sec.

One of the major advantages of cable technology is its ability to climb gradients with slopes as high as 100 percent or greater. Non-cable-propelled people mover technologies are limited to much lower maximum gradients of between 10 percent and 15 percent, which has a potentially significant advantage, for many urban centers within North America that have slopes exceeding 15 percent. However, general awareness of cable technology among transportation planners and engineers, architects, and land developers is limited. Research was conducted to identify and characterize available cable technologies and their application potential for urban environments.

CABLE TECHNOLOGY

The vehicle in a cable system is attached to a cable that runs in a loop between pairs of stations. Motion is imparted to the vehicle by means of the cable, the velocity of which determines the velocity of the vehicle. This moving cable commonly is referred to as a haul rope. The drive motor or motors for the cable are located at one of the terminals and usually are DC motors. The cable that moves the vehicle is wrapped around one or more large wheels called drive bullwheels, which are linked to the drive motor either directly by a shaft or via a speed-reducing gearbox.

Tension is maintained in the cable either by weights or by hydraulic or pneumatic tensioning devices that act on one of the bullwheels. The tension placed on the bullwheel creates friction along the points of contact between the cable and surface of the groove in the bullwheel, which permits the force developed at the rim of the bullwheel to be transferred to the cable and used to move the vehicles.

When the rope needs to be decelerated under normal operation, it is necessary to slow down the drive motor by reducing the amount of current passing through it. Regenerative braking also may be used. Physical braking devices are used for other than normal stops—namely service and emergency stops. The devices frequently consist of disk-type brakes located on one of the bullwheels that are powered by the drive motor. Emergency brakes also may be located on the vehicles. Along the guideway and in the stations, the position of the cable is maintained by sheaves or pulleys over and under which the cable runs. The cable is made from wire strand, is available in a number of diameters and wire configurations, and usually has a core made of a synthetic material such as polypropylene. The cable also may serve as an antenna to transmit voice and signal communications between the vehicle and central control room or terminal.

Some systems with suspended vehicles may use a second type of cable as a track to provide only support for a vehicle. Called a track rope, the cable is stationary and relatively stiff compared with the haul rope. The track is made of elements having a complex geometric cross section that lock together and develop the stiffness in the cable. It is capable of supporting heavy weight and provides a running surface or track for small wheels attached to the hanger of the vehicle. The vehicle hangs beneath the track rope. Track rope also is manufactured in a variety of designs, diameters, and strengths.

On all systems, vehicles are passive and receive no electrical power for propulsion along the guideway. With some technologies, a power rail may be provided for door operation, air conditioning, heating, lighting, and, for one technology, air levitation of the vehicle (this adds to the cost, complexity, and weight of the guideway, however). If vehicles receive no power, doors are opened in stations either by means of mechanical linkages that engage the vehicle when it approaches

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the boarding area, or by means of on-board electric motors that receive power only when the vehicle is in its final stopped position and plugged into a power outlet in the terminal.

State-of-the-art cable systems feature fully automated vehicle-door opening and closing; vehicle start-up and acceleration; vehicle positioning and velocity control; vehicle spacing and headway control; vehicle deceleration and braking; and system fault or error detection, diagnosis, and response. On continuous systems, vehicles are launched automatically. Interval is controlled electronically. Doors are designed to open and close automatically.

Computers and software are used to provide command, control, and fault detection/response functions. Systems vary from vendor to vendor, but all check vehicle velocity and position, cable position, cable tension, status of motor, and all feature interlocks to prevent vehicle movement when unsafe conditions exist (e.g., open doors). All feature automatic application of service and emergency braking when system parameters warrant it. Some systems generate logs of system operation and downtown events. Technologies that have been developed in Europe have been subjected to European codes that emphasize safety.

CLASSIFICATION OF SYSTEMS

The origins of cable technology date back to the late 19th and early 20th centuries. Technologies for funiculars, gondolas, and reversible tramways evolved in the Alpine regions of Europe to meet the transportation needs of mountain areas. Today, these technologies find widespread application in ski resorts. The family of cable technologies can be classified by type of service and vehicle support technology, as shown in Table 1. The primary categories of service are reversible, continuous, and pulsed. Secondary categories of service are based on transport unit (TU) capacity.

Reversible systems feature transport units composed of single or multiple vehicles that shuttle back and forth between terminals at the ends of the line (Figure 1). Individual vehicles remain permanently attached to the cable and reverse direction at the terminals. Only one TU can run in each direction. System line capacity is dependent on system length, capacity of the TU, operating velocity, and station dwell time. Frequency of departure and wait time are dependent on system length, operating velocity, and station dwell time. Cruise velocities of present reversible systems range from 23 to nearly 40 ft/sec.

Continuous systems feature transport units that detach from the cable in stations for passenger loading (Figure 2). Single-vehicle TUs are launched from the stations automatically at preset intervals on a continuous basis. The haul rope moves continuously at a constant velocity. When launched from a station, a vehicle is accelerated to the velocity of the cable and attached to it via grips. On entry to a station, the procedure is reversed. Vehicles are unclamped from the haul rope and decelerated. Acceleration and deceleration are accomplished by frictional forces developed from a series of tires or belts that engage the clamping device or undercarriage of the vehicle. At terminals, TUs are turned around so that they always run in the same direction, rather than also running in reverse. System line capacity is dependent on the capacity of the transport unit and the headway or interval between units. Headways as low as 8 sec can be achieved for four- and six-passenger vehicles, and cruise velocities of 16 to 20 ft/sec

TABLE 1 CLASSIFICATION OF CABLE SYSTEM TECHNOLOGY

Type of Service and Vehicle Support	Small TU (4-14 pass)	Medium TU (15-49 pass)	Large TU (50-169 pass)	Very Large TU (≥ 170 pass)
Reversible-Bottom Supported				
Levitated		Otis Shuttle	Otis Shuttle	
Pneumatic Tire			VSL Metro Shuttle 6000	
Steel Wheel		*Funicular	Funicular	Funicular
Reversible-Suspended				
Cable Guideway		*Tramway	Tramway	
Rigid Guideway			Waagner-Biro Monorail	VSL Metro Shuttle 6000
Continuous-Bottom Supported				
Pneumatic Tire		Poma 2000	(Poma 2000)	
Steel Wheel	Soule SK	(Soule SK)		
Continuous-Suspended				
Cable Guideway	Detachable Gondola	Detachable Gondola		
Pulsed-Suspended				
Cable Guideway		Non-detachable Gondola	Non-detachable Gondola	

* TU capacity is smaller than typical for this type of technology; few examples exist
( ) Technology under development

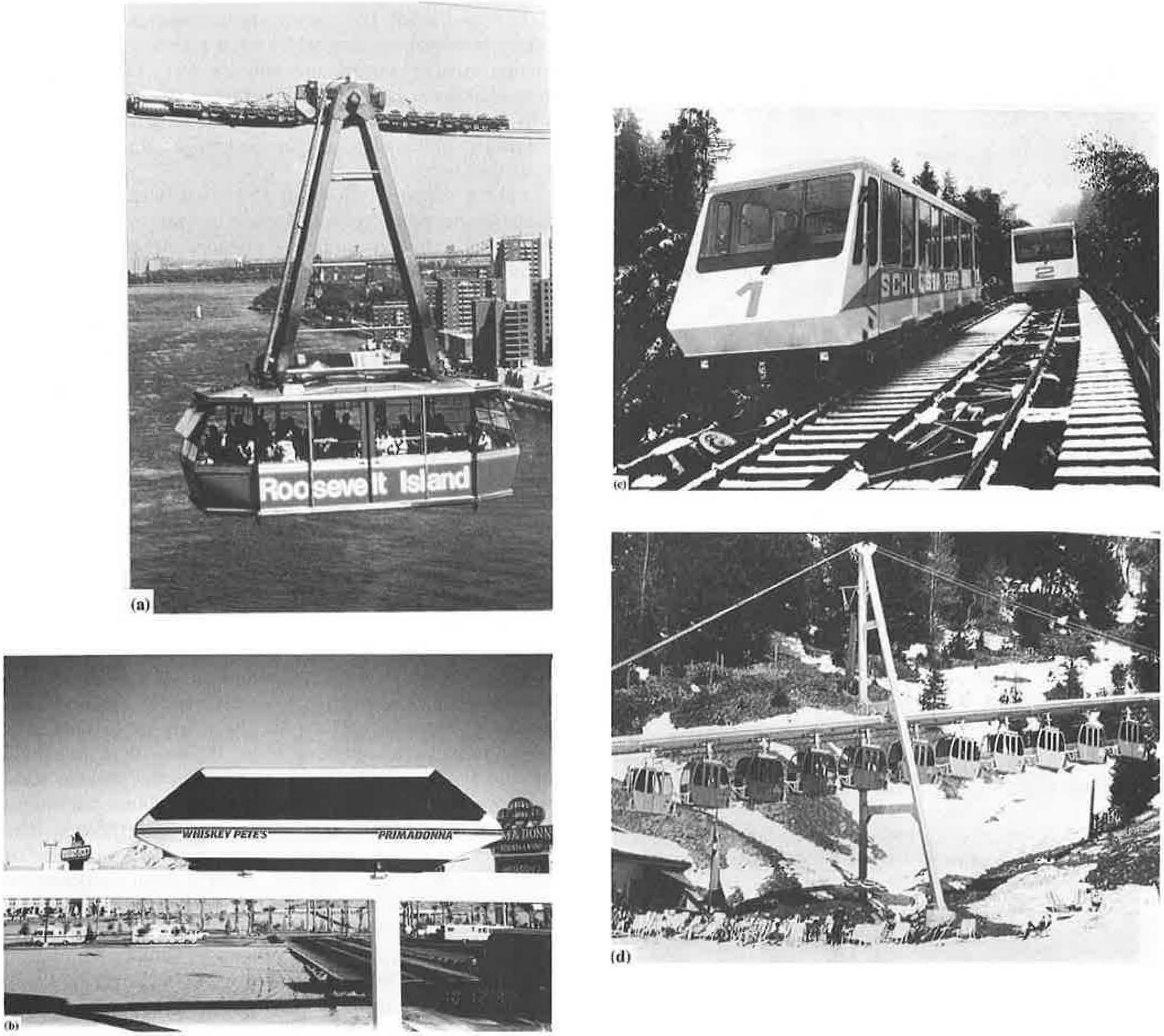

FIGURE 1 Reversible systems: *a*, suspended vehicle cable guideway tramway system (courtesy VSL); *b*, bottom-supported pneumatic tire shuttle system (courtesy VSL); *c*, bottom-supported steel wheel funicular system (courtesy Waagner-Biro); and *d*, rigid guideway suspended system (courtesy Waagner-Biro).

are typical. Multiple TUs run in each direction at the same time. Frequency of departure and wait time are not dependent on system length, operating velocity, or station dwell time.

Pulsed systems combine features of both reversible and continuous systems (Figure 3). Transport unit capacities are high and consist of a series of small vehicles assembled into trains. The haul rope does not reverse direction at the terminals. It moves in only one direction, turning the TUs around in the terminal. The cable is slowed or stopped to permit passenger loading in the terminals. Two or more TUs are attached to the cable. Every time a TU passes through a station, the cable is slowed or stopped. Because of this, hourly system capacity and wait time are a complex function of TU capacity, distance between stations, operating velocity, station dwell time, and the number of the TUs relative to the number of station platforms in the system. Maximum cruise velocity is 23 ft/sec. Pulsed systems are staging a comeback on European ski slopes. An advantage of the pulsed system over a reversible system is that more than two TUs can be operated at one time, thereby increasing frequency of departure and reducing wait time. An advantage over a continuous system is a much simpler mechanical requirement since vehicles do not need to be accelerated or decelerated independently of the haul rope or attached and detached. This simplified mechanism offers potentially lower capital and maintenance costs. However, station locations must be planned carefully. If they are not equally spaced, TUs will stop between stations. Also, capacities are relatively low.

The vehicle size categories used as the secondary variable for classifying type of service are based on the desire to dis-

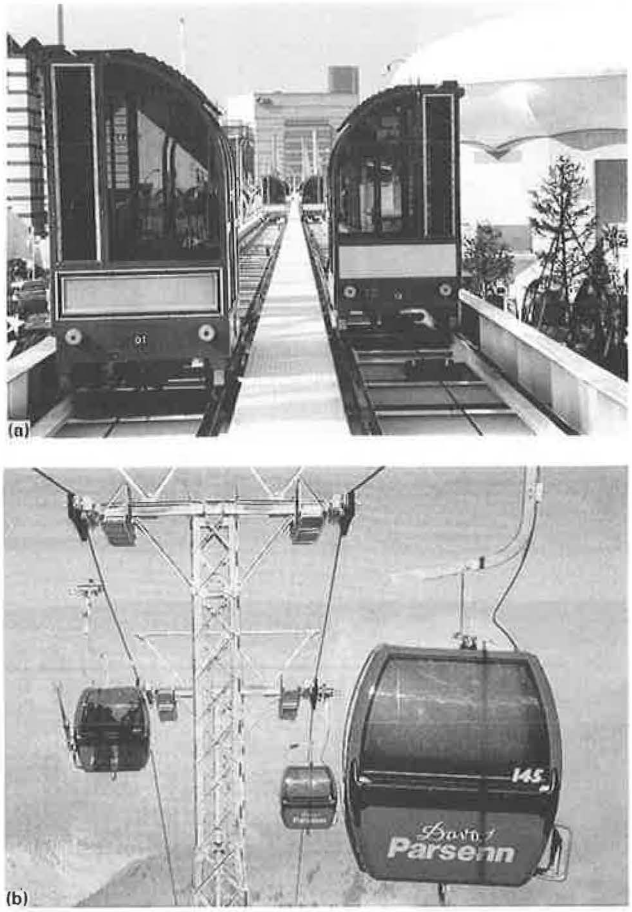

FIGURE 2 Continuous systems: *a*, bottom-supported system (courtesy Soule); *b*, suspended vehicle cable guideway gondola system (courtesy vonRoll).

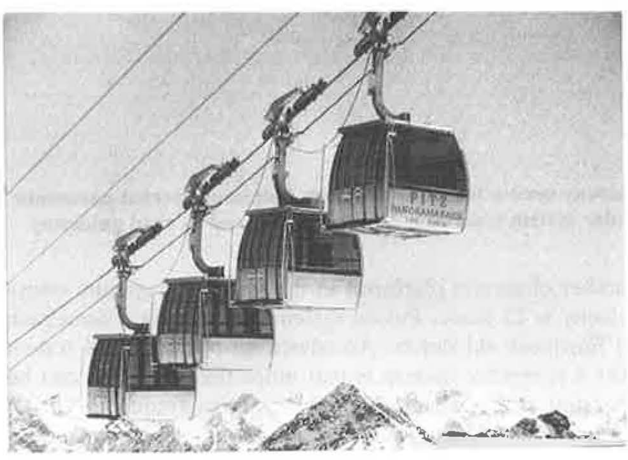

FIGURE 3 Pulsed system (courtesy Waagner-Biro).

tinguish between technologies that offer smaller, more "personalized" vehicles from technologies that carry large numbers of people in single vehicles. The upper boundary of 14 passengers for small TUs was chosen to include the Soule SK system in the small vehicle category. The next boundary of 50 passengers per TU was chosen to distinguish between typical capacities for detachable and nondetachable TUs. The final boundary of 170 passengers was chosen to mark the upper boundary of reversible aerial tramway TU capacity among existing systems and indicate that TUs for existing funiculars have capacities much higher (there is no reason why larger capacity TUs could not be developed for aerial tramways, although passenger loading and unloading problems could occur).

Vehicle support technology defines a third classification variable. All cable technologies can be grouped into either a suspended or bottom-supported category. Among the existing suspended systems, all but two installations feature cable guideways. The cable guideway technologies have evolved to serve mountain transportation needs that involve steep gradients and chasms. Cable guideways leave a very small footprint and are relatively inexpensive. Rigid suspended guideways are more expensive to construct; the amount of additional expense depends on span length and load.

Among the systems with bottom-supported vehicles, three types of technology for the vehicle/guideway interface have been developed: levitation on a cushion of air, pneumatic tires, and steel wheel/rail. All use a guideway structure made of steel or concrete. The levitation and pneumatic tire technologies were developed for urban activity center markets and relatively flat terrain. The steel wheel/rail systems were developed for mountain applications and steep gradients. Many are placed in tunnels.

Table 1 also reveals combinations of types of service and vehicle support technology for which no systems presently are available. For example, the family of reversible systems is shown to be larger and cover more TU sizes than the family of continuous systems. Table 1 also indicates that no technology presently is being marketed that combines continuous service with vehicles suspended beneath a rigid guideway. The table reveals a lack of available systems featuring large or very large detachable vehicles, either bottom supported or suspended, and continuous service. Presently, one technology, the Soule SK, is being adapted to penetrate the boundary of this market area by means of a larger vehicle. Another of the technologies listed, the Poma 2000 operating in Laon, France, also is at the boundary of this market area.

GENERAL PERFORMANCE CAPABILITIES

As a generalization, given state-of-the-art design, the family of technologies fits a niche characterized by peak-hour demands of between 500 and 3,500 passengers per hour per direction per line, route lengths up to 3 mi, and three stations. Each of these values is dependent on the particular cable technology; some of the technologies could not achieve both the system length and capacity maximums simultaneously. However, these values can be achieved with off-the-shelf, presently available technology.

Figure 4 shows capacity versus system length characteristics for over 100 existing cable systems. Many of the gondola, tramway, and funicular systems represent ski area applications. The figure indicates that both funicular and gondola systems have been used to satisfy the simultaneous needs for high capacity and long travel distances over 10,000 ft; however, gondolas offer superior service because of their higher frequency. Pulsed systems have been used for long distances

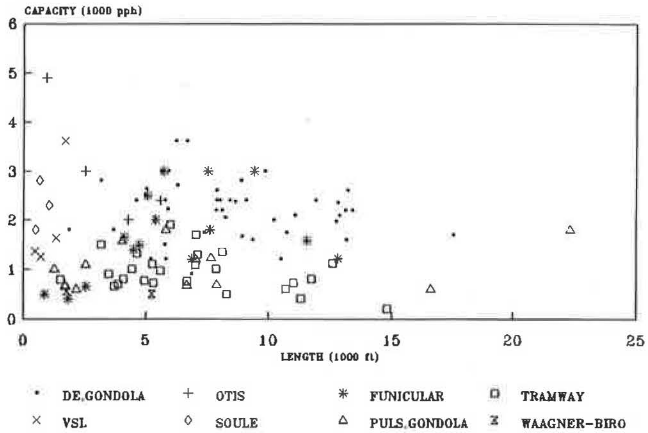

FIGURE 4 System length versus capacity.

combined with low passenger volumes. The bottom-supported technologies used in urban areas, as represented by the VSL, Otis, and Soule SK systems, tend to feature higher capacities and shorter system length of up to 5,600 ft.

Maximum velocities among the various classes of technology typically are as follows:

Class	*Maximum velocity (ft/sec)*
Reversible, bottom-supported	39.4
Reversible, suspended	32.8
Continuous, bottom-supported	18.0
Continuous, suspended	19.7

These speeds are adequate for many of the short distance applications for which cable technology is best suited. To exceed these velocities would require further research and development and, quite possibly, result in significant increases in the cost of system components. Considering cable technology in general, the upper limits of velocity are influenced by rope dynamics and safety. Higher speeds require more complicated design of equipment, such as acceleration and deceleration devices, bullwheels, and sheaves. The cost of design increases rapidly with increases in velocity.

Alignment capabilities vary from technology to technology. Suspended cable guideways are best suited to straight alignments. Horizontal curvature of suspended cable guideway systems can be achieved only with additional significant expenditure for land, structures, and mechanical systems. A common technique is to derope and decelerate the vehicle, shunt it around the horizontal curve on a rail at a reduced velocity, accelerate it back to haul rope speed, and reattach it to a second loop of cable for the next tangent. These actions are carried out in an angle or deflection station. However, the Waagner-Biro Suspended Reversible Monorail features a fixed guideway consisting of an I-beam approximately 0.92 ft by 0.92 ft, which lends itself easily to tight horizontal curves; radii as low as 328 ft have been used. The bottom-supported technologies all feature horizontal curvature, though minimum feasible radii vary from system to system. The minimum radius for the Otis system varies from 125 to 500 ft depending on the length of the vehicle; the Soule and VSL technologies can achieve 100-ft-radius curves. The Poma 2000 features a radius of 262 ft on unsuperelevated track and 131 ft on superelevated track. Horizontal radii for funicular systems tend to be large, however, because of the suspension systems on the vehicles and the lateral forces created by the rope and vehicle. Radii of horizontal curvature of existing funiculars range from 1,047 to 1,640 ft.

Ability to climb gradients varies dramatically among the systems. The suspended cable guideway systems easily can achieve gradients of 100 percent or more. The Waagner-Biro Suspended Reversible Monorail features a 37 percent gradient. Funiculars have been constructed with gradients exceeding 70 percent. Aside from the funiculars, other existing bottom-supported technologies have lower maximum gradients, partially because of vehicle floor design. When gradients exceed 15 percent, vehicle floors may have to be redesigned to accommodate passenger comfort needs. Otis installations feature gradients as high as 8 percent, though a 5 percent maximum is preferred. Soule claims that gradients up to 12 percent can be achieved, and VSL engineers state that 15 percent gradients can be designed. The Poma 2000 similarly claims to be capable of 15 percent gradients.

COSTS

Cable technology can offer a potential cost advantage because of several factors, all of which relate to the fact that the prime mover is stationary, rather than contained in each vehicle, and a cable is used to maintain vehicle position. This construction results in the potential for (a) less expensive and lighter vehicles as a result of the absence of individual vehicle-mounted propulsion units and computer guidance systems, and in most systems, absence of on-board heating and air conditioning units; (b) less expensive vehicles, resulting from lower cruise velocities, which reduce the costs of propulsion, braking, and suspension systems; (c) potentially lower guideway costs as a result of lighter vehicles and simpler guidance technologies; (d) less expensive power distribution requirements because of a lack of a need for a power rail in many systems; and (e) lower maintenance costs caused by simpler mechanical and electronic systems. Absence of a power rail also eliminates the risk of electrical fires in vehicles. Several suppliers of bottom-supported systems can provide a power rail if needed; they are necessary with the Otis technology to provide power for levitation of vehicles. Lack of heating and air conditioning in vehicles, however, can be a drawback during temperature extremes.

Availability of cost data is limited, making it difficult to compare the economics of the various cable technologies. Generalizations can be made, however. Guideway costs are low for the suspended cable technologies and involve only the support towers and cable. Most of the capital cost is associated with the terminals. For detachable gondolas, a rough rule of thumb is $5 to $9 million for a 1-mi system. A reversible tramway could be somewhat more expensive because of more massive terminals and machinery; in one feasibility study conducted nearly 10 years ago the cost of a 4,000-ft system was estimated at over $10 million. Most existing funicular systems have been built in tunnels and thus involve tunneling costs of between $800 and $1,300 per ft if boring conditions are good. Installed costs have been estimated as $1,500 to $2,500 per linear foot, or about $8 million to $13 million per mi for funiculars. Otis officials suggest that a 1-mi levitated system including civil works would cost around $14 million. Soule officials estimate that a 0.5-mi system would cost $4 million to $8 million exclusive of civil works. VSL reports that the 1980 cost of a 1,300-ft system was $3 million. Thus, a crude estimate of costs for a 1-mi system would be approximately $10 million plus or minus several million dollars depending on site characteristics and the particular technology.

APPLICATION POTENTIAL

Potential applications exist for several basic types of systems, including airports, feeders to regional rapid transit, downtown circulators, feeders to remote parking, internal circulation in large developments, and leisure facilities. The technology in its present form is not suited for line-haul service, for which buses, advanced light rail, rapid transit, and conventional rail systems are more appropriate. Also, system expansion can be costly and difficult unless anticipated and planned for during initial design.

An important capability of the suspended cable systems is their ability to span long distances without the need for supporting structures. Thus, they can inexpensively span rivers, highway interchanges, rail yards, and low structures. They are an inexpensive means of providing extra capacity across rivers and linking downtowns with redevelopment projects on the opposite side of a river. A second unique capability of aerial cable systems is their ability to ascend gradients as high as 100 percent. This enables them to provide people mover functions in environments in which no other technology would be satisfactory. A primary example is mountainside transportation or combinations involving rivers and mountainsides. Examples of this type of application can be found around the world in urban areas. Frequently, they involve leisure facilities that are major regional attractions and contribute to the local economy. An example is the reversible aerial tramway that ascends Sugarloaf Mountain in Rio de Janeiro.

A potential drawback of suspended cable guideway systems is the sense of insecurity they may generate among users. The experience of hanging from a single wire rope in a vehicle undergoing lateral sway and vertical oscillations can be frightening to those unused to it. Although danger is negligible, perceptions may suggest the opposite. The pervasiveness of this apprehension in American culture is unknown. Although this apprehension probably decreases with exposure, only those individuals who ski have the opportunity to become familiar with suspended cable systems. However, gondola systems that feature two or more haul cables have been developed (*2*). Multiple-haul cables increase the stability of the vehicles and produce a better ride quality. Bottom-supported systems, in contrast, project a strong sense of security. Also, they are less subject to service interruptions caused by weather conditions. Suspended systems, for example, must be shut down during high winds and electrical storms.

Airport Applications

For airport systems featuring terminal configurations that require only simple two-station shuttles, cable is appropriate. Given the short distances and lack of need for multiple station stops, cable technology may be able to provide nearly the same level of service as that of self-propelled vehicles. In fact, cable systems have begun to find applications in Japan, where one is being installed by Otis at Narita.

Feeders to Regional Transit

The use of people movers as feeders, an option that has been neglected in the United States, could encourage use of rail rapid transit and regional rail systems. Cable systems are being implemented in France by Soule for this purpose. A cable feeder line could connect a land use that generates a large number of trip ends (such as a hospital, university, government buildings, or an office center) and a transit/rail station that lies within about 1 mi. In the United States, one example of a cable system feeder can be found at Roosevelt Island, New York, where a reversible aerial tramway connects the island with a terminal in Manhattan. Passengers can transfer to buses at the terminal (*3*).

Downtown Circulators

Some downtown people movers are planned as one- or two-way loops that serve multiple stops. Cable technology may not be as well suited as self-propelled people movers for this type of configuration. However, configurations that can be planned as two or more separate lines that cross each other or touch at their endpoints might be suitable candidates for cable technology. Examples of proposals of the type that featured gondola systems include Kansas City, Mo. (*4*), and Santa Cruz, Calif., where a pulsed system was proposed (*5*). A bottom-supported reversible system has been constructed to connect Harbour Island with downtown Tampa, Fla. (*6*). A gondola system to access the Cincinnati CBD has been studied (*7*), as well as a reversible aerial tramway to connect Detroit, Mich., with Canada across the Detroit River (*8*). The difficulty associated with future expansion of cable systems, as mentioned previously, could be a potential drawback for their use as downtown circulators.

Feeders to Remote Parking

Another neglected option is the feeder from a downtown area to remote parking at the fringe of the CBD. A reversible cable system to serve this purpose has been studied for Pittsburgh, Pa. (*9*). A gondola system to connect Denver's Auraria Higher Education Center with remote parking facilities located at Mile High Stadium also was studied (*10*). Additional opportunities for remote parking feeders exist around freeway interchanges located at the periphery of the CBD. Airports may represent opportunities for connections between terminals and parking lots or rental car lots. Feeder facilities also may serve leisure centers.

Internal Circulation in Large Developments

Internal circulation systems in office complexes, shopping centers, residential developments, and mixed land use developments can enhance land values under the right conditions. The internal circulator also may connect to a regional transit system or remote parking and serve as a feeder. Large office parks present an opportunity for the use of people movers to eliminate the need for parking areas immediately adjacent to buildings. Parking lots can be located toward the periphery of the site, and the interior can be preserved for pedestrian walkways and green areas. This type of planning can enhance the appearance and environmental quality of the site and help achieve aesthetic objectives. Developments that feature vertical elevators in buildings may be potential candidates for horizontal people movers to link buildings together and to parking facilities. Examples of this type of application have occurred primarily in leisure facilities.

Leisure Facilities

Leisure facilities consist of public parks, theme parks, hotel/convention centers, resorts, and expositions. Systems serving these areas may provide internal circulation or link parking areas with major attractions. Most of the existing detachable and pulsed gondolas, reversible aerial tramways, and funiculars presently serve ski areas. Bottom-supported reversible systems also have been constructed at three hotel/casinos in Nevada and one in the Republic of Bophuthatswana in South Africa. Cable technology has been integrated architecturally in the hotel/casino applications. Terminals of the hotel/casinos are located adjacent to gaming rooms but could just as easily be located adjacent to lobbies. A bottom-supported reversible system is under design for the J. Paul Getty Museum in Los Angeles. Bottom-supported continuous systems have been employed at Expo 86 in Vancouver, B.C., the Yokohama Exotic Showcase Centennial, in Japan, and the Paris-Nord Exhibition Park in France. The Mississippi Aerial River Transit System, or MART, was a detachable gondola constructed to link the New Orleans World's Fair with remote parking on the opposite side of the Mississippi River (*11*).

CONCLUSIONS

Despite the relatively small number of existing urban applications, suppliers of cable technology are continuing to make design improvements that could expand market potential. Improvements include guideway design, a wider range of TU sizes, innovations in suspension, and adaptation of state-of-the-art command and control technology. On many recent bottom-supported reversible systems, the user may be unaware that the vehicle is passive and being propelled by a cable rather than by on-board electric motors. In terms of vehicle departure frequency, the continuous systems can provide a level of service that approaches that of personal rapid transit. Eight- or 9-sec headways are common for systems with four- to six-passenger vehicles. With vehicles this small and with headways this short, the development of an off-line station capability would result in personal rapid transit. One supplier has proposed this, but the concept has not yet been developed and tested (*12*).

Technological constraints vary markedly among the systems. The strongest potential market for cable systems may be new developments, where the numbers and locations of stations and the transportation system can be planned simultaneously with major buildings. This type of planning would enable accommodation of any of the technological constraints of cable systems. Pulsed technology could prove highly cost-effective under the right circumstances. Although station spacing is critical to the success of pulsed systems, it easily could be taken into consideration during the planning of new developments.

Available cost data are insufficient to draw any firm conclusions about the price competitiveness of cable technology versus self-propelled technology. Available data suggest that cable may have an advantage in terms of guideway and vehicle cost. Maintenance costs for reversible and pulsed systems should be low. Individuals trained to maintain elevators conceivably could be trained to maintain cable systems.

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