Implementation Problems of a Dual-Mode Guideway

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Certain specific problem areas in the implementation of a dual-mode transit system guideway indicate a need for close scrutiny of differences between standard highway design technology and dual-mode guideway design. One such area is choice of guideway surface materials and their effect on vehicle-guideway interaction characteristics and performance. Operating environment also imposes restrictions on vehicle performance and system capital expenditure by the need for adequate moisture removal techniques. Guideway intrusiveness and subsequent geometric constraints imposed by urban corridors with high-density land use affect performance and level of service since reduced turn radii in CBD areas affect vehicle speed and maneuverability within ride comfort and safety limits. Emergency operations and vehicle retrieval techniques must be carefully developed to minimize system downtime and maximize safety. Fail-safe principles must also be defined, for their interpretation affects system safety, operating procedures, and capital cost. Solutions to these problems must result in the development of system hardware consistent with dual-mode implementation philosophy.

The dual-mode transit system (DMTS) is a personal rapid transit system that combines features of fixed-route and demand-responsive bus systems with automated transit. Two primary modes of operation are used: a manual mode that requires an operator to drive the DMTS vehicle on the existing surface street network and an automatic mode that routes the vehicle via a dedicated guideway system through urban corridors to distribution points. Much information has been achieved from operation of bus transit systems through the years, but as yet little experience has been gained with the implementation and operation of high performance automatic bus vehicles on exclusive guideways.

A first step in development of DMTS is guideway design philosophy and identification of potential problem areas. Early examination of specific guideway design, operations, and maintenance problems and their effects on DMTS performance should help to alleviate costly redesign during implementation. Some major areas of concern, such as guideway materials, operating environment, intrusiveness, emergency operations, and fail-safe design, are reviewed here to illustrate the effects of design variations on performance.

GUIDEWAY MATERIALS

Selection of materials for construction of guideway support structure and running surface is currently influenced by highway design technology and operating experience. Skid resistance is one important system performance parameter directly affected by choice of pavement material. This relation is currently the subject of detailed study, for increased skid resistance requirements have been dictated by the surge in automatic transportation system development.

Skid resistance is defined as "the force developed when a tire that is prevented from rotating slides along the pavement surface. More commonly, skid resistance is thought of as a pavement property; it is the antonym of slipperiness" (1).

Pavement surface characteristics are one of several factors that affect the stopping ability of a vehicle on the guideway. The interactions among these factors are difficult to assess. Therefore, it is useful to describe the relation between the frictional resistance to motion and the applied load perpendicular to the interface between tire and pavement. The term "friction coefficient" is used to describe this relation, but precise pavement and tire characteristics must be known, along with speed, load, inflation pressure, temperature, and other details. Skid number is used to describe the friction coefficient for a specific set of these parameters.

The attained level of skid resistance is essential in the determination of headways for automatic transportation systems, such as DMTS, during on-guideway operations. The maximum design headway for DMTS is 1.5 times the safe stopping distance of the vehicle. The minimum headway (equal to safe stopping distance) is calculated by considering effects of brake lining, load, wind variation, control tolerances, and acceptable jerk rates, as well as attainable friction resistance. The effects of skid-resistance variations on headway for various operating speeds are shown in Figure 1.

Since DMTS performance and safety are dependent on the frictional resistance attained during vehicle-guideway interaction, a high and consistent level of pavement skid resistance must be attained. On the other hand, practical constraints on the economics of skid-resistance maintenance (i.e., how often pavement must be renovated or replaced) dictate attainable DMTS performance levels.

The two primary characteristics of pavement surfaces that most affect skid resistance are macrotexture and microtexture. Macrotexture is the roughness of the surface as a result of finishing (portland cement) or aggregate size (bituminous). This characteristic contributes a small percentage of the total attainable tire-pavement friction through resistance developed as the tire alternatively compresses and expands while riding over the surface. A most important contribution, how-

ever, is the provision by macrotexture of escape channels through which water may pass, allowing the tire to contact the pavement. This reduces the possibility of hydroplaning. Pavement grooving and increased porosity enhance this water escape and provide reservoirs to eliminate surface water film.

Microtexture describes the surface roughness of the individual aggregate and surface particles that provide for adhesion between tire and surface and is the larger component of friction. Microtexture can be quite variable, depending on the presence of loose particles (dust) or contaminants (bitumen, deicing materials).

Deterioration of skid resistance occurs through wear and polishing of aggregate, plastic smoothing (bleeding), rutting, contamination, and water presence. Effects of these actions depend on choice of pavement materials, amount of traffic, type of traffic, and seasonal effects. Large variation in skid number can also occur at different locations, even on new, unworn surfaces. In addition, estimation and measurement of pavement frictional resistance are not accurate to the degree required to predict surface performance characteristics with absolute assurance.

The individual pieces of aggregate in portland cement concrete (PCC) are supported by mortar and are not greatly subjected to traffic exposure. This reduces the effect of microtexture and related skid resistance. The high range of aggregate envelopment permitted by some types of asphaltic concrete (AC) surfaces results in a wide range of antiskid properties, depending on the nature of selected aggregates (aggregate selection obviously affects PCC skid resistance in a relative manner). The presence of excess bitumen at the pavement surface (bleeding) may cause plastic reduction in skid-resistance properties especially with the presence of water on the road surface.

Comparison of PCC and AC pavements reveals that both surfaces have initial skid numbers between 55 and 70 and both exhibit similar reductions in effective skid resistance with increased traffic accumulation (wear ratio). AC pavements are susceptible to wear especially where repetitive vehicle tracking occurs over the same surface area. PCC pavements generally exhibit service lives double that of AC surfaces, which is an additional economic consideration.

Pavement surface renovation may be accomplished by several means to increase skid resistance after wear and polishing have occurred. PCC pavement can be dragged (roughened), acid etched, grooved, or overlaid with a thin layer of aggregate. AC pavement can be grooved, overlaid with a thin bituminous binder, or heated and planed followed by "rolling in" a new layer of aggregate particles. The alternative to surface renovation is application of a new surface or seal coat.

Thus, pavement skid resistance places practical constraints on DMTS performance levels through maximum attainable skid numbers. Economic constraints are placed on maintenance of a high level of skid resistance through choice of materials and their effect on periodic surface renovation or replacement.

OPERATING ENVIRONMENT

During the automatic mode of DMTS operation, vehicles operate on a dedicated guideway separated from surface traffic, allowing this portion of travel to be completed with minimal trip times. Headways must be short to maintain adequate capacity and a high level of service. DMTS must be capable of reliable operation consistent with passenger safety and comfort under adverse environmental conditions. Trade-offs must be made between degraded operations and capital and maintenance costs required to maintain system capacity and level of service.

The primary environmental detriment to normal operations is the presence of moisture on the guideway, either in the solid or liquid state. Water may be present on the DMTS guideway running surface through one or a combination of several events: precipitation, rainfall, or snowfall directly onto the guideway; capillary action through guideway structure; or runoff from adjacent areas. The latter two events affect at- or below-grade guideway sections only. Parapet walls if included in the design should protect running surfaces from direct runoff. These walls, however, will provide little protection from drifting snow, especially in deep-cut sections (Figure 2).

The presence of moisture in the form of water film or runoff, frost, ice, or compacted snow degrades guideway skid resistance. This moisture also contributes to many maintenance problems through disintegration of pavement, erosion of subgrades, heaving of surfaces due to subsurface ice formation, and corrosion of supporting structures. Puddles on running surfaces may cause vehicle hydroplaning, and splashing may interfere with operating equipment. Ice or compacted snow contributes to vehicle lateral instability as well as altering vehicle vertical positioning on the guideway. Ice formation on steep grades inhibits traction and may prevent it entirely. Ice or frost formation on power and communication rails may prevent transfer of power or signals to the vehicle. It becomes obvious, then, that adequate snow removal, ice control, and surface drainage are necessary to ensure DMTS operation even in degraded modes.

Several methods of ice and snow control are available to DMTS: deicing chemicals, guideway heating, plowing, and frequent vehicle operations during the precipitation period. The least expensive method of control in terms of direct costs appears to be application of deicing chemicals. These chemicals, of which chlorides are the most popular, have corrosive side effects, attacking not only the pavement surface itself but also supporting steel structures. Moisture-laden air in the guideway vicinity can become saturated with chemicals and become corrosive to electronic equipment on board vehicles. Use of polymer seal coats, or membranes, has been studied to waterproof pavement surfaces, and more expensive chemicals are available with reduced corrosive characteristics (i.e., 15 times more expensive than salt). Sand may be used as a melting and absorbing device once precipitation has stopped, but then it must be removed from the dry guideway.

Electrical and hot fluid melting systems are available at a cost of from $0.3 to $0.5 million per guideway-mile, which involves embedding heating coils or pipes directly beneath the running surface for snowmelting. These systems provide adequate melting capability, but are subject to several drawbacks. Both systems require redundant sensing devices to detect surface temperature and moisture presence. Both require some warm-up time requiring forecast knowledge of weather conditions or constant system "standby" operations. Thicker pavement surfaces are required to house and protect these systems, and care must be taken to avoid rapid temperature changes and resultant thermal stresses in the pavement. These systems require frequent inspection and have high annual maintenance and operating cost, especially if local electricity costs are high.

Plowing or blowing of snow creates secondary snow-removal problems. Storage or other disposal means must be provided for dumping of plow-accumulated snow. Blowing may not be acceptable, depending on adjacent land use. Plowing often scrapes and wears the guideway

running surface. Conversely, compacted snow accumulates where the blade does not contact the surface. Sidewalls and power rails must also be blown or brushed clean. Plowing will be effective only as an auxiliary to some other method of snow control.

Compaction or removal of snow by traffic operations clearly is dependent on snowfall amount and composition and traffic frequency. Vehicle operations tend to compact snow and decrease friction, and, therefore, are not singularly effective in snow control. Application of sufficient chemicals to produce slight snowmelting will allow vehicles to clear running surfaces of compacted snow and ice. Under these conditions, frequent plowing will be required to augment slush runoff.

Since DMTS vehicles must also operate off the guideway on standard roadways, a problem arises when vehicles must be equipped with chains or studded tires to operate on roads during inclement weather. If guideway surfaces are kept relatively dry, chains and studs will cause rapid wearing of the pavement surface with subsequent high maintenance costs to retain required skid resistance and ride quality. Operational delay times to remove this equipment prior to guideway operations will be prohibitive.

Removal of precipitation (rain, melted ice, or snow) is accomplished by crowning of the road surface and by use of nonzero grade. Standard highway drainage techniques tend to induce free flow from the pavement centerline and away from the edge of the pavement. Since DMTS guideway is walled to provide vehicle retention, free flow away from the running surface may not be possible, and some method of drainage may be required. Care must be taken in the design of drainage systems so that

1. They do not allow water to flow freely from elevated structures onto adjacent property,
2. They will not be vulnerable to clogging from guideway debris or icing,
3. They can be easily maintained, and
4. They will not add unduly to structural requirements or detract from guideway structural integrity.

These requirements point toward the use of extensive drainage systems if normal system performance is desired during inclement weather.

INTRUSIVENESS

Implementation of a DMTS guideway in an urban CBD will involve coordination of guideway design geometry requirements with urban spatial constraints. DMTS interaction with land use involves infringement on building space, pedestrian walkways, and other transportation modal rights-of-way. The DMTS guideway will affect land use activities, such as reducing floor area and impeding pedestrian or traffic flow. In turn, physical constraints on these activities will alter DMTS guideway geometry and, therefore, performance.

The urban complex generally contains distinct residential, industrial, commercial, and administrative areas linked by arterial highways. These major streets provide logical mass transit routes for access to the CBD and determine the selection of routes for circulation and distribution within the CBD.

Major street right-of-way characteristics include space for pedestrian walkways, curbside parking, four traffic lanes, and, often, a narrow median strip. Typical right-of-way widths for four-lane major streets in CBDs range from 80 to 90 ft (24.4 to 27.4 m) A typical intersection is shown in Figure 3. This intersection is capable of handling within its right-of-way a DMTS guideway maximum radius of approximately 260 ft (79.2 m), depending on guideway width. Constraints of a typical urban intersection on guideway geometry and operating speed are given below. A typical urban intersection is considered to be four intersecting traffic lanes with parking and pedestrian sidewalks on both sides of streets (Figure 3). The maximum guideway superelevation is 0.1 ft/ft, and the maximum allowable lateral acceleration is 0.1 g.

Guideway Width (ft)	Max Turn Radius Through Intersection (ft)	Max Operating Speed in Curve (mph)
8	270.5	28.5
10	265.7	28.2
12	260.8	28.0
14	256.0	27.7
16	251.2	27.4
18	246.4	27.2
20	241.5	26.9

This will require the guideway to begin spiral transition at midblock, cross over one entire street right-of-way, and repeat this for the intersecting street (Figure 4). Guideway speeds for this radius will be limited to about 28 mph (45 km/h) at standard lateral comfort levels, which appears compatible with expected maximum operating speeds for DMTS in CBD applications. Geometric limitations, therefore, affect overall DMTS performance since compensation must be made for changes in maximum allowable line speed. Shorter turn radii will, of course, reduce allowable operating speeds; the lower bound is the turn radius of the vehicle itself. A 50-ft (15.2-m) guideway radius will allow operating speeds as high as about 12 mph (19 km/h).

Short-turn radii applications, such as in CBD areas that have high-density land use and at on- and off-guideway ramps, bring about clearance problems in addition to reduced operating speeds. These turning clearance problems are a direct function of vehicle design dimensions and maneuverability. Vehicle wheel base, width, body overhang, and turning radius combine to affect the minimum guideway width on curved sections. These effects are plotted in Figure 5 to show the required increase in guideway width with decrease in turn radius. An additional width factor must be applied during manual operations to allow for maneuverability.

Increased guideway width compounds DMTS intrusiveness and adds to the cost of materials and construction. Steerable rear wheels to eliminate off-tracking and reduced body overhang will greatly reduce width requirements but, in turn, may not be cost effective. Trade-off studies should be made to determine the desirability of complex vehicle design changes. Figures 6 and 7 show the effects of vehicle design and turn radii on guideway intrusiveness at a typical urban intersection.

DMTS stations feature off-line loading to avoid interference with vehicles bound for other destinations. Off-line station lanes incorporate acceleration and deceleration ramps so that vehicles may merge or diverge at line speed without affecting main-line traffic operations. The distance required to accelerate to (and decelerate from) line-haul speed is directly proportional to the desired speed. For example, the distance required to accelerate to 60 mph (96.6 km/h) at a constant acceleration of 0.15 g is 800 ft (243.8 m). If line-haul speed were reduced by half, to 30 mph (48.3 km/h), this distance would be 200 ft (61 m), a 75 percent reduction. The station lane length required for the 60-mph (96.6-km/h) case is 1600 ft (487.7 m), exclusive of berths and storage areas. Although this length has a substantial effect on guideway capital costs, the availability of land in dense urban

areas where stations will be required is of more importance. Intrusiveness of stations and the main guideway complex is also a critical factor in public acceptance of the system.

Figure 1. Headway traction relation.

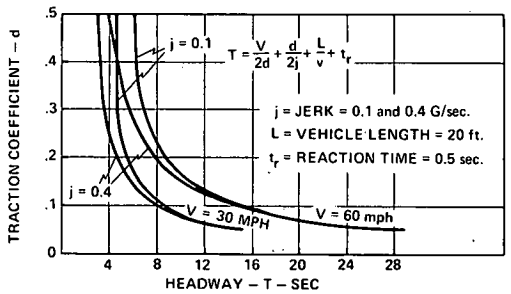


Figure 2. Snowdrift effects.

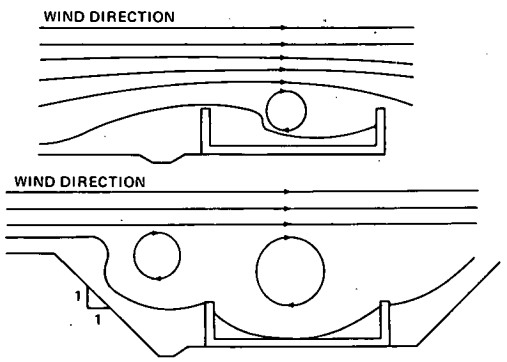


Figure 3. Typical urban intersection.

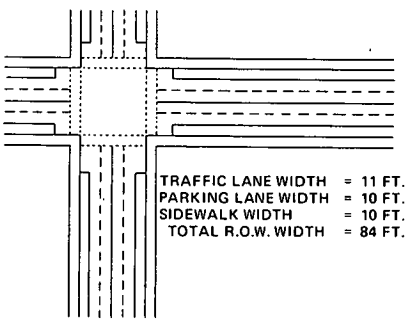
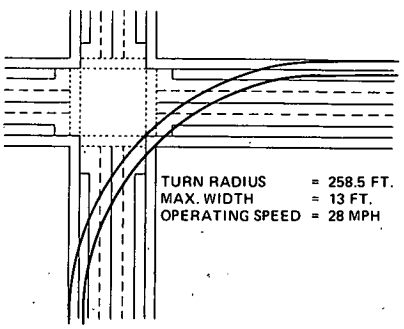


Figure 4. Maximum radius turn through urban intersection



EMERGENCY OPERATIONS

Malfunctions of DMTS equipment during normal guideway operations may be divided into three classes. Class 1 malfunctions are those that pose a threat to the safety or integrity of the vehicle or system and require an immediate and irrevocable stop. Class 2 malfunctions may affect vehicle safety, but the vehicle is mobile and

Figure 5. Turning radius constraints on guideway width.

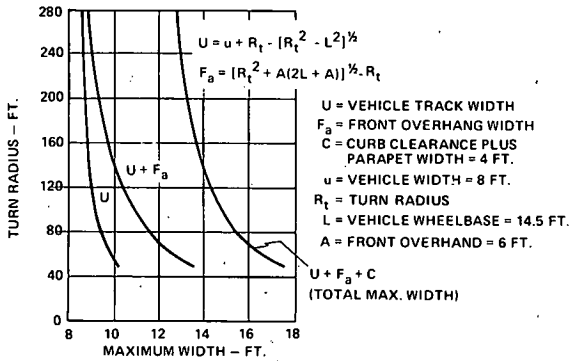


Figure 6. 90-ft radius turn through urban intersection.

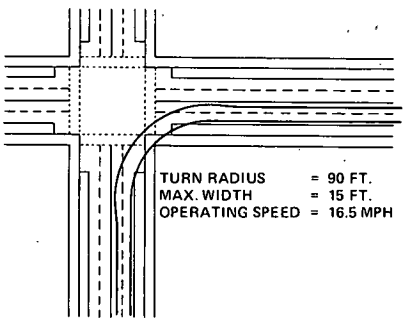


Figure 7. Minimum radius turn through urban intersection.

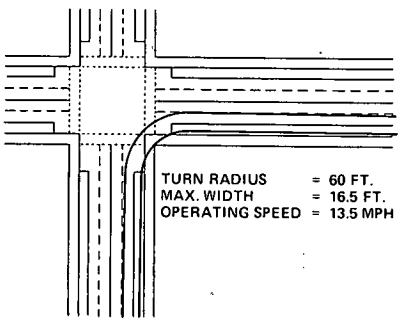
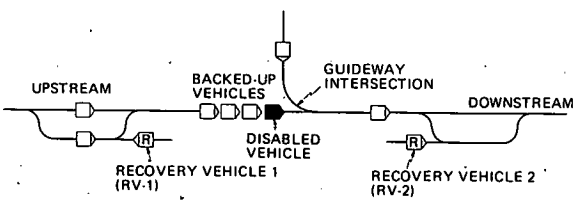


Figure 8. Disabled vehicle recovery problem.



can be routed (possibly at reduced speed) to the nearest station and removed from service. Class 3 malfunctions do not require immediate action, and correction is discretionary. Class 1 malfunctions are of primary interest in guideway implementation since emergency operations are required to retrieve the vehicle (and passengers) from the breakdown point with speed and efficiency.

In an urban fleet, an average transit bus will require road-call maintenance for all malfunction classes about four times a year. Thus, one breakdown of one class or another per weekday could be expected in a fleet size of only about 80 buses. One breakdown per peak hour of operation might be expected for a fleet of 800 buses. Bus maintenance data vary widely among transit properties, but such data are believed to be of the correct order of magnitude for comparison with dual-mode vehicles even when supplied with high-quality electrical and mechanical components and serviced with diagnostic equipment. However, it is not clear how these will affect breakdown rates.

In the event of an accident during guideway operation (67 percent of operating time), such a vehicle collision with a guideway structure, associated structures, or another vehicle, or in the event of a safety-related system malfunction requiring vehicle stoppage on the guideway or station, power should be removed where applicable from that section or sections of guideway involved. Emergency procedures should be developed to evacuate passengers from the disabled vehicle or to recover the disabled vehicle or to do both so that there is a minimum disruption of normal system operation.

Under negligible and marginal hazard conditions, passengers should preferably remain in the vehicle until the vehicle recovery operation is complete. However, under critical or catastrophic conditions, such as fire, passengers should be evacuated from the guideway in an expeditious and safe manner. For this purpose, the vehicle should be equipped with an interlock to interrupt guideway power whenever vehicle doors (normal or emergency exit) are opened on the guideway. In addition, each powered guideway section should be equipped with an adequately marked emergency exit located where no powered section of guideway can be encountered during the evacuation operation. Safe methods of egress from the guideway would allow transfer of passengers from the disabled vehicle to another form of ground transportation, saving as much as one-half the recovery waiting time.

Depending on the degree of emergency or disablement, DMTS vehicles can be recovered by manual control (driving the vehicle), remote manual control, automatic operation restart, towing or pushing by another DMTS vehicle, towing or pushing by a guideway service vehicle, or hoisting from guideway. If the disabled vehicle is driven, towed, pushed, or hoisted, then it must be accessible either along the guideway or via the street system surrounding the guideway. All methods will require detection and location of the disabled vehicle within the system, alerting and briefing of maintenance crew (located either centrally or at a number of stations), access to guideway with maintenance vehicle (or direction on street network), travel to breakdown site, assessment of the nature of the emergency, and towing or pushing the vehicle to the nearest station where passengers may disembark. This must be accomplished in a reasonable period of time.

Automatic system restart and rerouting is the most expedient form of recovery with the best chance of minimum downtime for the system. The ability to perform this action, however, is least likely of the recovery methods. Remote manual control requires no vehicle access, but vehicle speeds during recovery will be necessarily low since direct observation of the disabled vehicle en route may not be possible and damage or degree of malfunction may not be ascertainable. Manual drive-off is the simplest form of recovery, but requires time for the driver to enter and take control of the vehicle. After control is gained, the speed attained en route to the nearest station depends on the nature of the malfunction.

Towing or pushing by another DMTS vehicle requires either remote manual operation and safety system override or guideway access and manual driver operation. This, of course, ties up two carloads of passengers. For expedience, guideway service vehicles and maintenance crews must be strategically located at station or guideway vantage points.

A typical vehicle recovery problem involves a vehicle breakdown somewhere between service vehicle locations along the guideway (Figure 8). Suppose several vehicles are backed up behind the disabled vehicles blocking recovery by the upstream recovery vehicle (RV-1). Further suppose that a guideway intersection is downstream of the blocked vehicle, between it and the downstream recovery vehicle (RV-2). It may not be possible to reverse the backed-up vehicles past the position of RV-1 because of the upstream traffic. Then, the downstream portion of the guideway and intersection (initially unaffected by the blockage) will have to be shut off or degraded so that RV-2 can backtrack for recovery. Towing operations may require the recovery vehicle to back up during one-half of the trip, a difficult maneuver for a driver on a narrow guideway.

Hoisting the vehicle from the guideway as a standard recovery technique is prohibitive in terms of time and passenger safety. It is doubtful that a DMTS will have the required equipment for this operation at each maintenance area.

Recovery methods are rated by time and person-hours as follows:

Recovery Technique	Recovery Time	Person-Hours Required
Driver manual	3	3
Remote manual	2	1
Automatic restart	1	1
Towing or pushing by DMTS vehicle	4	1 or 2
Towing or pushing by service vehicle	5	2
Hoisting from guideway	6	4

Type of recovery is, of course, related to the class of malfunction. All DMTS systems should have the capability for automatic restart or remote manual control after class 2 malfunctions. Therefore, the various methods of towing, pushing, or hoisting become competitive for class 1 malfunctions.

Users of the system should be afforded adequate fire, medical, and security protection services through provision of special fire-fighting and ambulance vehicles and security forces if necessary. Local public services (fire department, hospital, police) should receive special training for emergency access to the system and coordination of emergency and system operations.

FAIL-SAFE DESIGN

The principle of fail-safe design states that, whenever an equipment failure, external influence, or human error affects the proper operation of an element of the system, that element shall revert to a state known to be safe. This implies that any such failure of a transit system component will not be catastrophic to passengers dependent on that component for conveyance.

In reality, it is not expedient or economical to design

Table 1. Comparison of impact-attenuation devices.

Impact Attenuation Device	Configuration	Cost	Remarks
Barrel nest	50-gal drums arranged in clusters; successive crushing of barrels applies tolerable stopping forces	Relatively inexpensive	Sacrificial; must be replaced after maximum inpact; minimum control of initial deceleration level; step function based on number of barrels in first row of barrier
Sand containers	Plastic barrels filled with varying amounts of sand; vehicle energy is attenuated by displacement of sand	Relatively inexpensive	Sacrificial; plastic containers must be replaced; sand reusable; fair control of initial deceleration by placement of smaller containers first; heavy (equal to vehicle weight)
Sand bumper	Sand pile poured on guideway; energy absorption by sand compression and shear	Inexpensive	Reusable; good control of initial deceleration through sand tapering; vehicle transfers kinetic energy to potential energy by riding up on sand pile and may become unstable; heavy; subject to moisture absorption changing deceleration levels
Shock absorber type	Mechanical truss with hydraulic or pneumatic shock absorber	Expensive	Reusable; high initial deceleration; substantial damage expected to vehicle

Note: 1 gal = 3.8 dm^3.

systems entirely to this principle. Most systems, therefore, are examined for "high risk" components, and these are designed to be fail-safe. There is, then, a group of low-probability failures that can occur with possible catastrophic circumstances. In some of these areas, it is possible to design for certain "last-ditch" efforts that will reduce the effects of these low-probability failures.

One of the more serious problems of automatic transportation systems is impact with guideway intersection gore areas (switch frogs). Another, less likely, event is overrunning stub-ended guideway segments. Both of these situations represent probable head-on collision between the DMTS vehicle and guideway civil structures. Therefore, some form of impact attenuation is required to reduce impact loads on vehicle structure and passengers to within tolerable limits.

During recent years there has been considerable interest and activity promoted by the Federal Highway Administration toward the development of impact-attenuation or energy-absorption systems. These systems are to be placed in proximity to fixed objects along the Interstate highway system to reduce accidental impact deceleration forces to within human tolerance levels. These devices have definite applicability to DMTS guideway gore areas and open-ended guideway segments.

This impact attenuator is the final safety device that will retain or restrain the vehicle on the guideway in the event of failure combinations, such as service and emergency brake failure or switching and emergency brake failure. Therefore, attenuators should be designed to arrest a vehicle moving at system speed.

FHWA currently permits an average vehicle deceleration limit for attenuation devices of 12 *g*. This greatly exceeds the deceleration rate of an automobile in an emergency stop (0.6 *g*) and would be catastrophic to mass transit standees, whose instability limit is about 0.5 *g*. Because of the nature of double failures necessary to cause high-speed impact, some compromise between normal deceleration limits and the FHWA criterion should be chosen for the design criterion.

Several types of reusable and sacrificial attenuation devices are available with widely varying characteristics and costs. Some applicable devices are given in Table 1.

CONCLUSION

Dual-mode transit system guideway design and implementation are heavily dependent on the knowledge and experience gained through the development of highways and motor vehicles. However, a need clearly exists for fresh thinking about design, operation, and maintenance problems specific to DMTS deployment. Solutions to some of these problems, such as materials, environment, operations, and safety, will directly affect the shape and performance of DMTS and the course of its development.

REFERENCE

1. Skid Resistance. NCHRP, Synthesis of Highway Practice Report 14, 1972.