Public Review Draft

Survey of Transit Technologies

Prepared for:

Sound Transit

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Appendices

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* Bucher, Willis & Ratliff Corporation produced the information in Appendices B, C and D under a separate contract. PB Farradyne was not involved in the preparation of these materials, other than to assist Sound Transit to format and assemble the document.

Introduction

The *Sound Transit Survey of Transit Technologies* was performed to assist Sound Transit with long range planning activities. It provides a resource for assessing the range of transit vehicle technologies to consider for application in a specific corridor. The sections comprising this survey include:

1. A description and review of transit technologies in use today,
2. A list of enhancements to transit technologies currently in development, and
3. Recommendations and criteria for applying transit technologies in specific corridor settings.

Appendices to this document include:

- Vendor information about deployed technologies referenced in this report,
- A compendium of transit vehicles and systems that have been proposed but not deployed*.
- Expert Review Panel comments on transit technologies
- A glossary of terms used in this document

The technologies described in this survey are at various stages of development and implementation. As this survey evolved, different reports were provided to distinguish between those transit technologies that are deployed in revenue service, and those which are still in concept, testing or small scale implementation. Oversight from an Expert Review Panel (ERP) provided meaningful insight and direction to support the data gathering and organization of this review.

Around the world there is a great diversity of transit treatments, and they have evolved to respond to an equal diversity of local challenges and preferences. Despite the fact that each transit technology has its proponents, no one technology is appropriate for every application. Ideally, each transportation technology and mode will be applied where it is most effective, but other factors come into play as well, including an agency's interest in maintaining compatibility between its services and managing its risk, and a community's preferences and tastes, image and identity.

For any one region, technologies need to be chosen that meet both system and corridor needs. This document identifies the range of technologies that may have application in future phases of Sound Transit implementation, and factors that should be considered when determining which technologies are candidates for application in a specific corridor context.

RISK AND NEW TECHNOLOGY

A key objective for this survey was to assess the types of new technologies that should be considered for future phases by Sound Transit. When a transit agency is a pioneer, advancing an unproven technology, the risks are significant. The vendor may not be able to deliver the goods, the cost may be higher than expected, and the new technology may not perform as advertised or be able to be maintained, extended or replaced. All of these can be costly both financially and politically.

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To minimize risk, two conditions must be met before taking a risk on new technologies:

1. The new technology must provide a clear functional benefit that current technology cannot, including the ability to deliver current functions more safely, reliably, or at less cost or impact, and;

2. A proven supplier must be making a significant investment to bring it to market. New technology is seldom specified by a transit agency unless a supplier has vigorously offered it. Risk is substantially reduced if the technology has been in successful operation in similar operating conditions on another property.

The vehicles, systems and technologies that currently meet those criteria are identified and included in the main body of this report, and fall in the categories of "deployed technologies" and "advances to deployed technologies." Appendix A includes representative samples of vendor materials and specifications for deployed vehicle technologies mentioned in the body of this report. Appendices B, C and D include a catalogue of proposed "alternative" transit technologies, including vehicles and vehicle systems, waterborne technologies and component technologies. Those technologies meeting the two conditions listed above are included in the main body of this report. The appendices document the range of proposals that has been surveyed to arrive at the more limited set of enhancements currently relevant in the Puget Sound context, and the many different technology-related initiatives and ideas that have been proposed to improve transit.

HOW TO USE THIS DOCUMENT

The first two chapters include a survey of technologies, and enhancements to technology under development, that are available to transit systems today or will become available soon enough to consider. Chapter 3 addresses issues to consider when applying technologies to corridor applications.

The primary purpose of this document is to provide guidance at the early system and corridor planning stage to identify the most suitable candidate technologies for a specific corridor application. Technical information will help system planners to identify factors that may become more important as more detailed analyses are conducted subsequently, and to identify promising developing technologies that should not be precluded early in the planning process. Considerations and criteria are presented that can be incorporated into corridor planning or procurement decision processes as appropriate.

A secondary purpose of this document is to serve as a resource for anyone who is interested in knowing the range of technologies that are currently in use or development, as well those that have been proposed and imagined around the world.

1. Deployed Vehicle Technologies

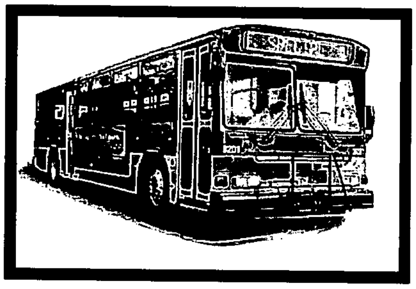
INTRODUCTION

This section reviews those vehicles that are in common use for transit applications. Technology changes typically result from improvements in existing designs, therefore the concepts included in this report should provide a sound basis for vehicle evaluations. Transit technologies have been adapted to serve diverse local conditions around the world, so there is often room to develop custom specifications using existing technologies before switching to a different generic vehicle technology.

When comparing vehicle technologies for a given task of moving passengers on a specific route at an average speed, several factors typically cause confusion. Seating arrangements are not similar. Car structural design standards are not similar or standard, in most cases. Top speeds are shown that may be of limited value due to a possible unsatisfactory ride quality, that can only be evaluated by riding the vehicle in question. The specific headway (time span) between trains and passenger waiting time should first be carefully evaluated because it impacts many issues, such as car fleet quantity, energy cost, and acceptability of vehicle designs.

Future increases in route passenger capacity should be considered. Interchange requirements with other routes is an issue. The use of equipment that is of a unique nature and that can only be obtained from one supplier can impact parts availability and future route expansions. Passenger boarding, with ADA factors considered, can impact vehicle selection. Many car and system design details are not provided here, only those parameters that affect the basic application of each concept.

This chapter describes categories of transit vehicle technology that are most useful to compare when addressing specific corridor applications. There is considerable overlap between them, especially when every customization option is considered, but these categories represent the most commonly accepted technology definitions in use. Detailed representative vehicle specifications provided by vendors are provided in Appendix A.



BUS

Features

A conventional bus will be an important part of all transportation systems, because it provides the gathering function from lower passenger density routes as well as circulation within local areas. Buses are also used to serve regional and intercity trips.

A bus route capacity is limited by the fact that buses cannot be coupled together to provide higher passenger density trains. Bus speed and passenger capacity are also limited by the traffic that shares its route. A conventional bus can be purchased in about any length from 22 feet to 40 feet. A single or double articulated design can also be used, with about 20 feet added for each articulation. Similar to other vehicles, bus passenger capacity can be increased by removing seats, using a longer design, and reducing the headway (operating time) between buses. Bus Rapid Transit (BRT) systems may combine all of these features to maximize passenger capacity.

Bus performance depends greatly on the operating environment. An HOV lane permits a higher average speed. An exclusive bus lane is a further improvement. However, the selected headway must be reviewed very carefully to ensure that it is practical, considering possible temporary operating obstacles, and turnaround requirements at termini. An operating problem must not cause a system shutdown.

A bus can use many energy sources, with a variety of transmission systems. The ratio of available horsepower to loaded vehicle weight is a measure of the bus performance. Alternative designs are briefly discussed in the following.

Vehicle Properties

CONVENTIONAL BUS

Typical parameters are; 40 feet long, 8.5 feet wide, 27,000 lbs. empty, 55 mph top speed. 40 seated (2x2 seating), 15 standees (at 4 per square meter), 15% grade capability, 275 engine horsepower, 9" boarding level from ground, 38" floor level from ground, 6 tires. The conventional diesel engine can use several alternative fuels, with fuel cost and engine maintenance being key considerations. Compressed natural gas is widely used with a large fleet in Atlanta and locally at Pierce Transit. Low-sulfur diesel fuel and particulate traps are being improved to also reduce emissions. Major maintenance items are engines, transmissions, and tires. With a special guideway not required, this is the lowest capital cost technology, although investments to isolate buses from the effect of other traffic can reduce the cost differential. Operating costs vary and can be found in available US government statistics.

Passenger capacity on a single bus route using standard 40' buses is 1650 people per hour per direction (pphpd) with 2 minute headway, and 825 pphpd with 4 minute headway. Articulated designs will increase the capacity, as will seat reduction to increase standees.

ARTICULATED BUS

The design used for this category is the New Flyer Industries Galaxy D60, single articulated, diesel engine powered bus. Typical parameters are; 60 feet long, 8.5 feet wide, 10 feet high, 40,600 pounds empty weight, 60 mph top speed (typical, varies with transmission and tire selection), 64 seated, 48 standees, 15% grade capability, 330 engine horsepower, 41 feet turning radius, Detroit Diesel Series 50 engine with Allison transmission, 3 doors on one side only, 10 tires, center axle drive.

Passenger capacity is 3060 pphpd with a 2 minute headway and 1530 pphpd with a 4 minute headway.

BRT (BUS RAPID TRANSIT)

BRT is a flexible form of rapid transit that combines transit stations, vehicles, services, running way, and ITS elements into an integrated system appropriate to the market it serves and its physical environment. This is not a technology issue; it is an operating concept that uses a bus to mimic a fixed guideway service, with short operating headways, a dedicated right-of-way, and reduced seating. BRT uses vehicles that may be driver-steered, guided mechanically or electronically. It can be incrementally implemented in a variety of environments, from totally dedicated to transit (surface, elevated, underground) to mix with other traffic on streets and highways or in HOV lanes.

Articulated designs (longer bus) are used to increase passenger capacity, including 80' double-articulated buses used in Curatiba, Brazil. Quoted passenger capacity for that system appears to be inflated if US levels of passenger comfort are desired. A key issue is the possible future conversion of the dedicated guideway to higher passenger capacity technology. A busway is an equivalent form of BRT. Ottawa and Pittsburgh have busway operations. BRT is operating in Curitiba, Brazil, Bogota, Columbia, Los Angeles, and other places.

Actual passenger capacity can be estimated as follows. Assuming an optimistic application that uses an 80' double articulated bus, two options can be considered. One option would assume a US style interior with 2x2 seating that could be assumed to accommodate 80 seated and 40 standing for a total capacity of 120. The second option would assume no seats with two standees replacing each seat for a total capacity of 200 passengers. With a two-minute headway for the first option providing 30 buses per hour per direction, the route capacity is 30 x 120 = 3600 pphpd. With a headway of one minute this increases to 7200 pphpd; such headways are not achieved except on dedicated busways or where multiple routes operate along a freeway without stopping. For the second option the respective capacities are 6000 pphpd and 12000 pphpd. These capacities are far below those quoted even with an unacceptable lack of seating. Of course, if the passenger standing density is increased to a very high level, an LRV competitive capacity becomes available. These passenger densities are acceptable in many other countries, but have not been accepted in the US.

Alternative Fuels

Several options are available, with some having been purchased in quantity and others still being developed with test units in service. Deployed technologies are shown below. Technologies being developed include fuel cells, and hybrids. These and other bus technology developments are discussed further in Chapter 2. The fuel source does not change the bus passenger capacity. However performance and especially life-cycle-cost may change dramatically due to the power source selection.

TROLLEY BUS

This technology is successfully operating in Seattle. It is an excellent concept with good acceleration, lower maintenance requirements (no engine or mechanical transmission), no emissions from the bus, and several available suppliers. It can maneuver from the running path to the curb for passenger boarding. Items of concern are the visual impact of the double wire overhead power line (especially at an intersection), the high cost of the bus (due to the small US market), the relative cost of diesel fuel vs. electric energy that varies with operating location, and the cost and location of the power distribution system (substations and overhead power lines). Seattle experience is that trolley buses are well suited for climbing steep grades, and that they can have a longer life than conventional buses.

Seattle also has a dual-power version that can use an internal diesel engine or the external electric supply. This is the Breda design that was used to allow diesel buses to use the downtown Seattle transit tunnel without producing diesel fumes.

BATTERY/HYBRID POWER

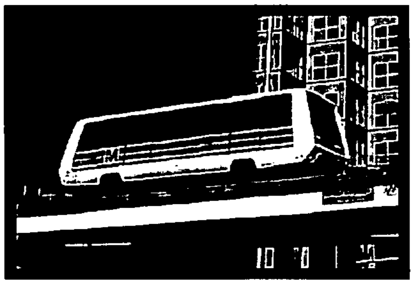
Shuttle buses have been supplied with battery power only to provide an emission free (at the bus) design. This concept is practical using a short length bus in a low mileage application. For conventional bus service the hybrid concept combines a battery with a small diesel engine. Battery life-cycle-cost is a key consideration, considering battery charging expense, battery replacement life, and the reliability of the drive motor and control system. A key operating issue is the comparison of the added first cost of the hybrid bus versus the savings in fuel consumption. Metro and Sound Transit recently demonstrated two hybrid buses, and Metro is considering purchase of additional hybrid buses to operate in the downtown Seattle transit tunnel, replacing the existing fleet of Breda dual-power buses.

While a dual-power bus uses either one of two separate power sources, a hybrid bus typically uses two internal power sources at the same time. In most cases, the battery provides the high current required by the electric propulsion system during bus acceleration. The parallel connected engine-generator set provides power to charge the battery and to provide the relatively low power required during speed maintaining. The key design feature is the extended life (mileage) that the battery can provide under these operating conditions.

The conventional 275 hp engine and transmission are replaced with an electric drive that uses AC induction motors that drive the powered wheels through individual gearboxes. A smaller engine that drives an electric generator is used as the parallel power source. Modern prototypes have been in test since 1995. A 1999 test program, that was managed by the Northeast Advanced Vehicle Consortium, provided comparison test data for conventional, CNG, and Hybrid bus designs, that included fuel economy and emission results. Summary information is available.

ENGINE FUELS

A modified diesel engine can also use other fuels to reduce emissions. This includes compressed natural gas, liquefied natural gas, liquefied petroleum gas, ethanol, and methanol. CNG has been widely used because it is cost competitive. A large fleet operates in Atlanta, and Pierce Transit operates a fleet of CNG buses. Key considerations for evaluating this alternative are cost, safety, engine maintenance, and operating range. The cost evaluation should also consider the need for a new fueling station.



PEOPLE MOVERS

Features

The "features" of this concept are difficult to review because many designs have been sold and many other designs have been suggested. Appendix B includes many of the proposed designs. Generally this concept uses rubber tires for car propulsion, support and guidance, a concrete guideway with DC or three-phase AC power supplied as part of the guideway, and a control system for automatic operation.

Operation is typically in a shuttle mode, at short distances and relatively low speeds (20 to 35 mph). Airports and activity centers are primary users of this concept, because the small cars allow a small clearance envelope that reduces construction expense. This concept has also been used for downtown city circulators, such as are used in Detroit, Miami and Jacksonville. Cars can be coupled to form higher capacity trains. Station doors are used for passenger protection. Very few, if any, seats are provided due to the very short trip times.

When considering this concept, two existing systems are suggested for evaluation. The original Westinghouse system has been used at many worldwide airports and is now available as the Innovia, supplied by Bombardier (Adtranz). The VAL system is used at the Chicago Airport and at multiple locations in France. Monorails are also used to provide short distance shuttle service. The VAL system and monorail are shown as separate technologies because they are also capable of being configured to provide medium capacity transit over distances typical of urban transit application.

Information for the Innovia system is provided in the following. A unique alternative automated people-mover is the cable hauled vehicle supplied by POMA-OTIS. It has been used in airports and activity centers and is currently available.

Two major issues are often ignored when considering people mover designs. A subtle issue is the consideration of perceived personal safety due to possible interaction with others, and the lack of a driver. People use small elevator cars because they have no choice and fellow passengers typically work in the same building. Also, the elevator entrance is within a building, generally not seen by casual travelers, with building security personnel often visible to the traveler. An airport system offers similar condition. Similar conditions are not provided by a people mover that is serving city streets. In addition, the smaller the car, the less "protection" is perceived as available from fellow travelers.

The second major issue is the unique nature of the people mover hardware. Every supplier offers equipment that is not offered by any other supplier. Vehicles and guideway design are key issues. When future system extensions are required the only choice for equipment purchase will be duplicate equipment from the original supplier, with price and availability being possible concerns.

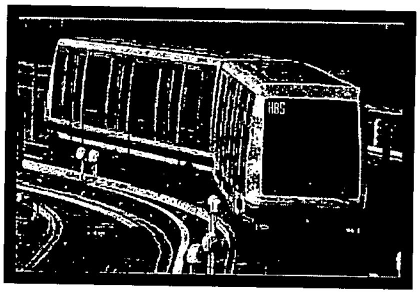
Vehicle Properties

INNOVIA

This rubber tired, electrically powered car can operate as a single car or as a four car train, using a center vertical beam for guidance, with four tires providing guidance and eight tires providing propulsion and vertical support for each car. This design supersedes the CX-100.

Car parameters are as follows: 39' 3" long, 9' 4" wide, 11' 1" high (a four car train is 157' long), empty weight 28600 lbs., maximum operating speed of 50 mph with a typical operating speed of 35 mph, 8 seats, 92 standees, max grade 10% with 6% suggested, high platform boarding at 43.3' above the running surface with two doors per side, min horizontal curve of 72' 6", min vertical curve of 360' sag and 450' crest. A fully automated system is used with the power supply being either 750 v DC or 600 v AC three phase, located at the guideway. AC traction motors are used.

This concept, in its older form, is in use in city circulators, such as in Miami, and at many worldwide airports. Passenger capacity with a four car train is 12,000 pphpd with a two minute headway, and 6,000 pphpd with a four minute headway.



VAL

Features

This rubber tired, electrically powered car was first introduced in Lille, France and is now operating in six other cities, as well as the Chicago O'Hare airport, and the Taipei city transit system. As a city service it is believed to operate a maximum of 32 kilometers, therefore it can be considered to be a "minimetro". The Model 208 is the latest design, using the married pair concept (two permanently coupled cars). A maximum train uses three married pairs or six cars. Each married pair uses eight tires for support and propulsion, with eight tires used for lateral guidance that operate on a vertical surface that is located at the outside of the guideway. A steel rail is also provided for switching. The VAL concept is provided by Matra, now owned by Siemens. VAL can be configured as a people mover, or to provide medium capacity transit over distances typical of urban transit application.

Vehicle Properties

A married pair has parameters as follows: length of 85' 9" (three MP 257'), width 6' 10", height 10' 10", empty weight 62000 lbs., Max speed is 50 mph with operational speeds of 35 to 40 mph, 38 seats, 122 standees, high passenger boarding at 45.7' with six doors per side, minimum route curvatures requirements not known. A fully automated system is provided that is reported to use a 90 second headway that can be reduced to 60 seconds. The 750 vDC power system is located at the guideway.

Passenger capacity with a six car train (three married pairs) is 14,400 pphpd with a two minute headway, and 7200 with a four minute headway. VAL shows relatively high passenger capacity due to the use of very few seats. Note that a three-married-pair train is only 10 feet shorter than a three-articulated-car LRV train that has many more seats.

MONORAIL

Features

This rubber tired vehicle concept became famous with its operation at Disney Resorts. The latest US order is an extension of a Las Vegas system. The design offers an attractive vehicle with the undercarriage not visible, and a low cost guideway if operation is to be shuttle service only. This concept is otherwise similar to other fixed guideway technologies, which can also be elevated but which use more standardized switches and other system components. Modern monorails can be configured as a people mover, or to provide medium capacity transit over distances typical of urban transit application similar to VAL and Skytrain.

Two design concepts are used. The ALWEG concept straddles a concrete beam using 10 to 20 tires per car, depending on the supplier. The SAFEGE concept is supported from an overhead guideway and uses 18 tires per car. Many suppliers have systems installed worldwide. The major North American supplier is Bombardier. Hitachi is a major Japanese supplier with several systems operating in Japan and one in Okinawa. US installations are approximately 5 miles in length. The Japanese installations vary from 5 miles to 10 miles in length. Each elevated guideway is typically separated from the opposite direction guideway, therefore minimum guideway surface area is required.

For longer or more complex systems, monorail systems require special adaptations to operate with system failures. A transit system is typically designed with many crossovers between the two "guideways" to permit reverse direction operation to bypass stations or track sections when required for operational problems or maintenance activity. Monorails provide route switching using large guideway sections that either move horizontally or rotate in place. A simple shuttle-type monorail typically does not use switching for normal passenger operation. In addition, a passenger walkway may be required along the guideway to permit passengers to exit the vehicles if there is a safety related problem. Adding these features to a monorail guideway may eliminate its advantage of a low cost guideway with minimum guideway surface area.

There are significant differences in the undercarriage (truck) design between the Bombardier and Hitachi cars. The Bombardier design results in a protrusion into the passenger compartment area that results in an unused space between cars, which also prevents passage between cars. The Bombardier design uses fewer tires than the Hitachi design.

Vehicle Properties

BOMBARDIER M-VI

The following parameters are provided for the four-car train that will be used in Las Vegas. The two center cars have different dimensions than the two end cars. Train length 137' 11", width 8' 8", height from guideway to vehicle roof 7' 9", empty weight 82,600 lbs. Max design and operating speed of 50 mph, 62 seats, 152 standees, max grade 6.5% (assumed propulsion thermal limit), high level boarding at 6 ¼ " above the guideway surface with one door per car side, minimum radius curves of 175' horizontal and 1000' vertical, 600v DC power at the guideway. A fully automated system is used.

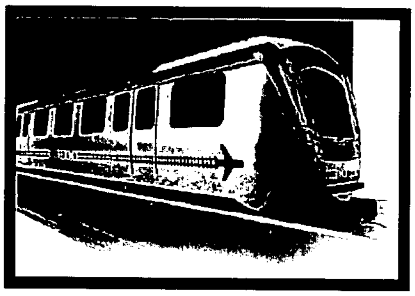
The 6.5% max grade is shown in the published vehicle specifications. As stated earlier, the rubber tired vehicle can operate on grades of about twice that of a steel wheel vehicle. However, another grade limitation is the possible overheating of the traction motors when operating on a sustained grade. A traction motor is typically duty cycle rated with acceleration and deceleration causing the major heating, as coasting or running at a constant speed, with no grade, is light duty. However, continuous constant speed running on a grade requires a higher power level. Therefore, A grade spec may show the peak grade that can be negotiated, assuming that it is relatively short with motor thermal overload not being an issue, or it may show the grade on which continuous operation is possible as limited by the motor heating.

Passenger capacity of 6420 pphpd with a two minute headway, and 3210 pphpd with a four minute headway.

JAPANESE MONORAILS

Two recent designs operating in Tokyo are the Series 1000 and the Series 2000, with both supplied by Hitachi. The Series 2000 has higher performance and a longer train and is used for the following car parameter definitions. The Series 2000 uses a six car train, 307' long, 10' wide, 9.76' above the guideway, empty weight 311,000 lbs., max service speed of 50 mph (max design speed of 55 mph), 210 seats, 390 standees, 6% grade, high level boarding at 23.6 " above the guide beam with 12 doors per side per train, 20 tires per car (120 tires per train), minimum radius horizontal curve is approximately 230' on the mainline and 150' in the shop area, 750 v DC is provided at the guideway.

Passenger capacity is 18,000 pphpd with a two-minute headway, and 9,000 pphpd with a four minute headway.



SKYTRAIN

Features

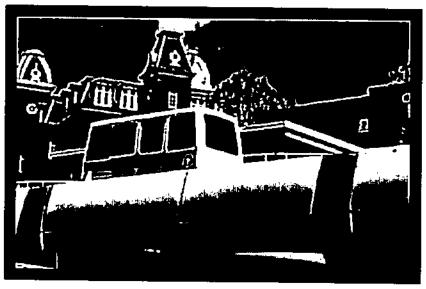
This steel wheel, electrically powered design uses conventional track and a two-power rail system. It offers a small cross section to reduce the cost of tunnels and the impact of elevated structures. Bombardier provides the cars and system. This concept has been provided to Vancouver, Toronto, Detroit, Bangkok, and Kuala Lumpur. A larger car design is being supplied for the new JFK Airport access system. Skytrain uses a 23" wheel diameter to reduce vertical clearance, and a linear induction motor (LIM) for car propulsion and electric braking, with the reaction rail located between the rails of the standard gauge track. This concept improves the traction motor reliability, however, it operates at a lower efficiency than a conventional rotary motor. The linear motor does not have bearings and therefore will have reduced maintenance cost. The truck uses a steerable axle design. This concept has been in service since 1986. An automated, driverless system is typically provided. Skytrain is functionally similar to automated guideway transit (AGT) technologies such as VAL and monorail, but the definition of AGT is usually limited to rubber-tired systems.

Vehicle Properties

The second generation MK II vehicle, as recently supplied to Vancouver, will be used to define the car parameters. The minimum train has two cars, with the married pair concept used. The following parameters are for a four-car train (two married pairs).

Length 227’ 8”’, width 8’ 8”, height 10’ 9”, empty weight 196,800 lbs., operating speed 50 mph (design speed 55 mph), 2x2 seating with 168 seats, 344 standees, 6% max grade, high level boarding is used with the floor level 31.5’ above the rail, two two-axle trucks , minimum horizontal radius of 115’, 600 v DC is provided by two separate power rails that are located at the side of the track structure. A fully automated system is provided.

Passenger capacity is 15,360 pphpd with two-minute headways, and 7680 with four-minute headways.



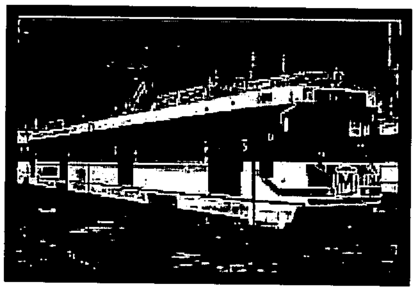
PERSONAL RAPID TRANSIT (PRT)

Features

PRT is an operating concept that is designed to permit a fleet of driverless cars carrying 2-4 passengers each to travel between any two stations automatically without making intermediate stops. Stations are off-line. A PRT system aims to replicate the flexibility of the arterial street and automobile system, allowing people and goods to travel from point to point without needing to share the vehicle or navigate a complicated transit network. This point-to-point operating concept differentiates PRT from people movers or other transit technologies. A station and guideway must be provided to all potential destinations, and a control system that will provide the complex switching and protection is needed.

The only deployed PRT system is at the campus of West Virginia University at Morgantown. Opened in 1975, the Morgantown system includes 8.7 miles of guideway, 5 stations, and 71 vehicles connecting the main downtown campus with the Morgantown CBD and two suburban campuses. The Morgantown system differs from a true PRT concept because cars are larger, accommodating 8 seated and 13 standing passengers, it is a linear alignment rather than a grid system, and because it is sometimes operated as scheduled service making all stops, depending on demand. Average daily ridership is 14,000, and design capacity is 3600 pphpd.

Raytheon invested several million dollars to develop a PRT concept called PRT 2000, but ceased development in 1999. The company had a prototype test track and three test vehicles that passed a 2-year testing phase. Despite having several interested potential buyers, none was willing to be the first to deploy the concept, especially since cost increases reduced the likelihood that a system could break even as originally hoped. Proponents of PRT have formed the Taxi2000 Corporation, and hope to raise funds to demonstrate a pure PRT concept. Academics differ over whether costs can be low enough and headways short enough to deliver the financial and ridership benefits that proponents expect.



LIGHT RAIL

Features

Due to the worldwide popularity of this concept it offers the most design alternatives. In the US there are single cars (Philadelphia), single articulated cars (several locations), and 70% low floor cars with double articulation (Portland, Boston, Northern New Jersey). These designs are discussed here. In Europe there are additional designs in service, such as, multi-articulated train, 100% low floor, and modular designs. Similar, but smaller designs used in Europe, for lower passenger density routes, are called Trams.

The light rail vehicle (LRV) can operate at street level, having a typical minimum horizontal curve radius capability of 85' with designs also available with a 45' radius curve negotiation capability. Track brakes are provided (electromagnetic brakes that clamp onto the rail head) to supplement wheel and motor braking and provide a high deceleration rate (6 mphps) that is needed to operate with auto traffic. Power collection is from an overhead wire that does not interfere with ground traffic.

High and low level passenger boarding is available, with the latter available using car steps or a low-level car design. The car floor can be 70% low level or 100% low level. A low floor design improves passenger access, but results in car subsystems being mounted on the roof, a maintenance consideration. While the 70% design offers conventional powered trucks (car undercarriage), the 100% design requires very unique truck designs and related motor mounting arrangements. The LRV also operates with high-level platforms, similar to that used by "subway cars".

Top speed has typically been 55 mph, however new designs (Houston) have a 65 mph capability. An LRV can be coupled into trains, with the car quantity limited by city block lengths and intersection considerations, platform length, or trainline voltage capability. The LRV can be provided with a variety of seating arrangements, however, 2x2 is typically used that results in a lower passenger capacity per train length than a vehicle that is designed for standees. Train length is easily changed by coupling cars together, with no change in train performance.

Vehicle Properties

CONVENTIONAL WITH SINGLE ARTICULATION

The Salt Lake City design is used for this parameter definition, with the maximum train length of four cars. Low-level boarding is used with steps to access the high interior floor. Train length 321.6', width 8' 8", Height to roof (w/o pantograph) 10' 10", Pantograph working range approximately 13' to 22.3', empty weight 352,000 lbs., Max speed 55 mph, 256 seats using 2x2, 480 standees, 10" from top of rail boarding with steps to 39' interior floor, 16 doors per train side, two axle trucks, minimum horizontal curve approximately 85', 750 v DC power is supplied from an overhead contact wire (catenary). Passenger capacity is 22,080 pphpd with two-minute headways, and 11,040 with four-minute headways.

LOW FLOOR , 70% DESIGN, TWO ARTICULATIONS

The Portland design is used for this parameter definition, with the maximum train length of four cars. The low floor design requires roof mounting of subsystem equipment with a corresponding increase in car height. Boarding is directly into the low floor area. Interior steps are used to access the high level interior sections at both ends. Train length 368', width 8' 9", height 12' 5" w/o pantograph, pantograph working height from 13' to 22' 4", empty weight 436,000 lbs., max speed 55 mph, 288 seats using 2x2, 468 standees, boarding at 14" above top of rail, interior steps to 39" levels at car ends, 16 doors per train side, conventional powered trucks (2) at car ends. Special truck at car center, minimum horizontal curve 82', minimum vertical curves of 820' crest & sag of1150'. Passenger capacity of 22,680 pphpd with 2 minute headway, and 11,240 with 4 minute headway.

COMMUTER AND INTERCITY PASSENGER RAIL

Features

The commuter rail concept is available in many forms for use in a metropolitan area system. It is also used in regional systems. Cars can be self powered designs (powered from an external electric supply), or they can be unpowered and hauled by an electric or a diesel-electric locomotive. Car designs can be single level, double level, or triple level, depending on needed passenger capacity and clearance restrictions. Car length is typically 85'. This is the only car concept that is regulated by the FRA railroad standards and industry used APTA Press Standard Guidelines, that include structural and crashworthiness design standards. Therefore, this concept provides heavier cars.

Cab signaling is required to operate over 79 mph. Train speed can be 125 mph with car designs approved for this speed. Speed is limited by locomotive horsepower and by the use of axle hung motors on US style diesel-electric locomotives (the latter limit is about 100/110 mph). Train speeds are also limited by local speed limits, which are influenced by the type of protection offered at grade crossings. Car passenger boarding can be low level with several steps (Kawasaki & Nippon Sharyo), or low level with one step or no steps (Bombardier, Alstom), or high level.

When the locomotive hauled concept is used the locomotive must supply electrical power to the trailing cars, Head-end Power. This requirement may limit the train size that may also be limited by the available length of platforms. The diesel-electric hauled train has been popular as it eliminates the cost of electrification. In the electrified Northeast Corridor, the electric locomotive hauled concept is used for new equipment. The electric locomotives used on the Northeast Corridor do not use axle hung motors, and operate at 125 mph.

A new concept now in intercity use by Amtrak in the Seattle region is the Talgo Train. This concept is unique in providing a passive tilt train capability, allowing higher speeds to be accommodated with existing railroad curve radii. It uses short articulated cars with single axle shared by the ends of interior cars. The US version is diesel-electric locomotive hauled. A high speed version is available for European Service. This design can be used for commuter service or regional service.

The commuter concept uses "coach cars" except for the trailing car that is a "cab car" (one that has a control station that is equivalent to that in the locomotive cab for opposite direction operation). Standees are typically not considered for commuter car operation, therefore, this parameter is not shown.

Vehicle Properties

SINGLE LEVEL, UNPOWERED

Many car designs using this concept are operating in the US. The Bombardier Comet IV, supplied to NJ Transit, is used for parameter definition of this concept. A single car definition is used, as train size is variable. Car length 85', width 10' 6", height 12' 8", max speed 125 mph (new designs only), empty weight 105,760 lbs. (cab) 101,850 lbs. (trailer w/toilet), 104 seats with 2x3 seating (cab car), 113 seats in trailer car, high level boarding at 51", low level boarding at 16" with steps to car floor, two doors per car side, minimum horizontal curve established when coupled to a locomotive is 315'.

Passenger capacity with a six-car train and no standees is 20,070 pphpd with a two-minute headway, and 10,035 pphpd with four-minute headways. However, commuter trains typically operate with much longer headways, of about 30 minutes, that would provide a capacity of 1338 pphpd.

BILEVEL, UNPOWERED

This concept is used in the Nippon Sharyo Gallery cars used by Metra (Chicago Commuter) and CALTRAIN (San Jose to San Francisco commuter). It is also used for the Alstom "Surfliner" cars that are in Amtrak service in Southern California. Amtrak cross country service uses the Bombardier "Superliner" design that has several interior configurations. The "Metra" gallery design is used for the following parameter definitions, based on a single car. The Gallery car does not have a full width upper level, with ticket collection available at the first level for both levels. Car length is 85', width 10' 4", height 15' 11", top speed 100 mph, empty weight 126,000 lbs. (cab), 122,000 lbs ((trailer), 145 seated (trailer car), 138 seated (cab car), low level boarding at 18" above top of rail with steps to 44" interior floor, single center door per car side with built in lift at one of the two entrance paths

Passenger capacity with a six-car train is 26,000pphpd with two-minute headways, and 1726 pphpd with 30 minute headways.

TRILEVEL, UNPOWERED

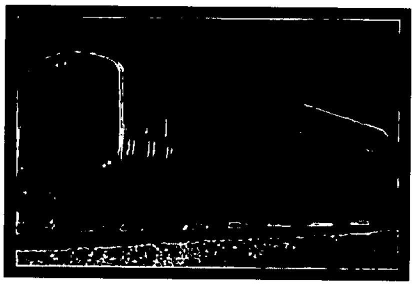
Bombardier and Kawasaki have provided this design concept, which has three distinct levels: one upper, one lower, and two intermediate at the car ends. Bombardier uses two quarter-point located doors per car side, with 17" boarding to the car first step. Kawasaki has provided high/low boarding and high-level boarding designs. Both designs have full width floors at all levels. With Sounder using the Bombardier design, it is used for parameter definition, on a single car basis.

Car length 85', width 9' 10", height 15' 11", empty weight 118,500 lbs. (cab car), 117,300 lbs. (trailer car), max speed 100 mph, 139 seated (cab), 148 seated (Trailer), lower floor height 25".

Passenger capacity for a six-car train is 26,370 pphpd with two-minute headways, and 1758 pphpd with 30-minute headways.

POWERED CARS

Many powered cars are also operating in the US. High level boarding, single level cars are powered from a third rail on the Long Island RR service. A single level car using high voltage AC power is used on the Montreal Two Mountain Line. Northern Indiana Commuter has bi-level cars operating from a 1500 vDC overhead line. The powered car, with its own propulsion system on the car, will be heavier, have better performance, and seat a few less passengers compared to the unpowered designs.



DIESEL MULTIPLE UNIT (DMU)

Features

This steel wheel car concept uses an internal power source and transmission, typically with one undercar mounted high-speed diesel engine used for propulsion, and a smaller engine used for auxiliary power. A mechanical or an electric transmission can be used. If a mechanical transmission is used with a single propulsion engine, one axle or two can be powered, depending on the supplier. If an electric transmission is used, two axles are powered with electric motors.

Originally this concept was provided by the BUDD Company about 50 years age, using their RDC design (rail diesel car). An overhauled version of this car is in use in the Dallas segment of the Trinity Rail commuter service. Modern versions of this concept can provide either of two basic car body designs. An FRA body strength compliant design has been offered by suppliers such as Bombardier and Nippon Sharyo, based on electric multiple unit cars that they have already delivered to North American commuter agencies. Smaller, modular designs are available from Bombardier, Alstom, and Siemens that have a much lower, FRA noncompliant car-body compression capability. This concept has been purchased by the new Camden to Trenton (NJ) Commuter Line using the Bombardier (Adtranz) GTW 2/6 design.

This concept does not require a wayside electric power supply. It is an alternative to the widely used locomotive hauled commuter car concept. Compared to locomotive-hauled service, the advantages of the DMU are that all vehicles carry passengers, the maximum axle loading is approximately one half that of a locomotive, the smaller engines are easier to maintain, the quantity of cars per train can be changed without changing train performance, the external noise level may be lower, and the fuel economy may be better. The DMU is attractive for lower density routes that require a short train of two to four cars.

However, this design concept has issues that should be carefully reviewed. For example, with engines on every car, the engine mounting to the car underframe must isolate engine-induced vibrations from the car interior. The engine exhaust system must be designed to eliminate exhaust noise and odor from the passenger compartment. The quantity of engines used per train should be carefully reviewed. If too few, performance may be inadequate. If too many, engine maintenance requirements may result in a high life-cycle-cost. Comparing horsepower per ton of train weight for alternative train concepts is a good preliminary step for determining performance equivalence.

Vehicle Properties

LIGHT WEIGHT, MODULAR DESIGN

This design is similar to the lightweight, modular designs recently offered for LRV's. The GTW model DMU offered by Adtranz (Bombardier) is used for the following parameter definitions. Designs are also offered by Siemens (Desiro) and Alstom (Coradia). While the GTW 2/6 was purchased for the Southern NJ project, the following description is for the GTW 4/8, because it offers the highest ratio of motored axles to total axles (0.5). For highest passenger capacity the GTW 4/12 should be used, a four car design.

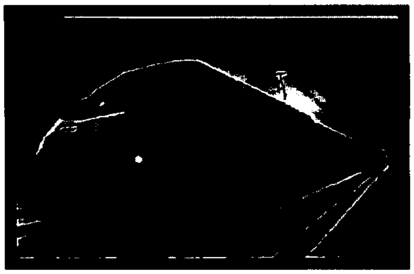
Train length 178.5', width 9.8', height 12.8', empty weight 168,000 lbs., max speed 60 mph, 202 seats using 2x2, 134 standees, max grade 6%, low floor design with 67 % at 22.4" above top of rail and 33 %

at 38.2 " above top of rail, three doors per train side, two axle truck using a "power car module" concept, min horizontal curve radius 132'.

Passenger capacity is 10,080 pphpd with a two minute headway, and 5,040 with a four minute headway.

FRA COMPLIANT DESIGN

This design has not been deployed, and is discussed further in Chapter 2.



HIGH SPEED RAIL

Features

CONVENTIONAL

This category can be confusing with regard to what it should include. Typically, a speed of over 125 mph has been used to define this category. Conventional steel wheel designs are operating or on order in several worldwide locations at speeds up to 175 mph. The speed is not equipment limited and 200 mph speeds are being tested. The speed limits have been due to ground vibrations and audible noise along the route. The Shinkansen (Japan), TGV (France), and ICE (German) designs are in service, with the lower speed Acela (Bombardier/Alstom) operating in the Amtrak Northeast Corridor Service. Talgo also has a high-speed design. The station spacing needed to achieve high-speed operation is only suitable for long-distance trips.

A key question when considering US high speed service, is not how fast can the train operate, but what is the optimum speed limit considering the economic factors. When operating and average speeds increase there will be an increase in ridership. However, this relationship in a new market is difficult to define. As train speed increases there will be a significant increase in life cycle–cost with track installation and maintenance cost, energy cost, power cost, and vehicle maintenance costs all increasing. Obtaining cost information as a function of operating speed is critical but very difficult to obtain for a new route. Vehicle properties are not provided because of the major differences in the designs. Project costs for high-speed rail networks have been in the range of 5 to 10 billion dollars.

MAGLEV

If speeds in the 300 mph range are needed and can be economically justified, the Maglev concept is the only available ground operating technology. The modern high-speed concept uses magnetic fields to support, guide, and propel a passive vehicle. It has not been proven in routine revenue service, having only operated on test tracks in Germany and Japan. Shanghai China has recently ordered a system from Germany, using the Transrapid design.

This concept is complex and cannot be discussed at length here, however, there are a few salient points that should be reviewed. The Japanese design requires the use of superconductivity, which will not be economically viable for some time. A complex power distribution system must be used as each vehicle must have its own power source in each controlling distance segment to externally control its speed in that segment using variable voltage and frequency. Operating cost information is not available for a regional system. First cost has only been estimates. The higher speeds increase energy and power costs to another level. With limited onboard power available, means must be reliably provided for vehicle onboard power for the electrical subsystems. Vehicle vibration and audible noise should be carefully reviewed.

FTA has proposed development of low speed maglev, however this appears to require a more complex power distribution system because vehicles will operate at closer spacing, with more power control guideway segments required. HSST, a Japanese maglev supplier, has been offering a lower speed design that uses an active vehicle, with a linear motor drive. This concept can significantly reduce the cost and complexity of the power distribution system. However, the issues of system efficiency and satisfactory vehicle power collection become important. The required peak operating speed will be the key issue in deciding which maglev concept will be satisfactory. Low-speed maglev is discussed further in Chapter 2.

HEAVY RAIL

Features

This concept is used to serve very high route passenger density requirements in the 30,000 to 50,000 pphpd range. Heavy rail cars can be short with a length of about 50 feet, such as those used in Chicago, Boston Blue Line, and New York City that use the R-142 design. Typically, especially for new starts, longer cars have been used with a length of 70 to 75 feet, such as BART, LA Red Line, Atlanta, and New York City that use the R-143 design. With subway operation typically used, power is provided from a third rail that is contacted by pickup shoes located on all powered trucks. The DC voltage provided is in the range of 600 to 1100 volts. Car design typically requires generous horizontal and vertical route curvatures that must be considered during the civil design. Platforms are level with the car floor. Maximum operating speed varies with the transit agency and the route, with typical speeds in the range of 55 to 75 mph.

In the past few years, two significant design changes have been provided for modern heavy rail cars that provide significant car weight reductions:

- An AC traction induction motor provides significantly higher performance (about 30%) in the same volume as that used by a conventional DC series traction motor. The recent NYCT car designs have used this feature to obtain a design that does not have all the axles powered, as a DC motor powered car would have. Therefore, the absence of the motor and gear unit reduces car weight. With unpowered axles the required adhesion levels are higher for a specific performance, however, AC propulsion has proven its ability to operate with higher adhesion requirements.

- The use of articulated car bodies that use a common truck is not a new concept, having been used on the TGV and many Light Rail cars. However, a new heavy rail car design, the C-20, from Adtranz (Bombardier) is operating in Stockholm using this concept that provides significant weight savings compared to a conventional truck arrangement. A key consideration for using this concept is the handling of separate cars in the maintenance shop.

In the 1970's decade, rubber tired heavy rail cars were provided for major transit systems in Paris, Montreal, Mexico City, and other locations. This design provided the typical advantages of rubber tires; higher adhesion, lower noise, and higher grade capability. However, this design also had disadvantages, which apparently resulted in its demise, as it has not been offered for about 17 years.

These disadvantages were as follows. A conventional steel wheel truck was also necessary to provide guidance through switches and during a tire failure, and to provide braking effort on the steel wheels that was not available with the rubber tires. This feature added considerable car weight. Tire operation on concrete is less efficient than steel on steel. This, along with tire flexing, added additional heat to the system. Typically, grades over 3% to 5% are not used in heavy rail routes, therefore the gradability is of questionable value. The noise reduction now has a reduced value with other means now available due to improved wheel and track designs.

In the following, performance information is provided for the New York City R-142 and R-143 designs as representative of modern heavy rail cars. Performance information is also provided for the 1974 rubber tired cars that were supplied to the Montreal Transit Bureau as an example of this design.

Vehicle Properties

NYCT R-142

This design uses 51' 4" long A cars and B cars that must both be in a train but not as married pairs. Four, five, or six car units can be used with A cars at both ends of a unit and B cars in between. A train uses two units. Only the A car has a full width operator's cab at one end. The A car has two fully motorized trucks (4 motors), and the B car has one of its two trucks motorized (2 motors). Friction brakes are installed on all trucks. High-level boarding is used in this subway system. The following parameters are based on a train using two 5-car units (10 cars), in an ABBBAABBBA configuration.

Train length 513 ft., width 8' 9 1/2 ", height 11' 10 5/8", empty weight 700,000 lbs., design speed 66 mph. service speed 55 mph, 376 seats using side wall bench seats, 1444 standees, boarding level of 44-3/4", 30 doors per train side, two axle outboard bearing fabricated steel truck, 90' minimum horizontal curve radius, +/- 2000 ' minimum vertical curve radius, 600 vDC third rail power.

Passenger capacity is 43,340 pphpd with a two-minute headway and 21,670 with a four-minute headway.

NYCT R-143

This is the first car fleet designed to use communication based train control (CBTC), a moving block "signaling" system. It uses 75 ft. cars with A and B cars in married pairs. Each unit uses an ABBA arrangement with two of these units per train providing an 8-car train. The following parameters are based on this train definition.

Train length 600', width 9' 11.7", height 12' 0.3", empty weight 662,400 lbs., design speed 65 mph, operating speed 55 mph, 344 seats using side wall bench seats, 1576 standees, boarding level approximately 44", 32 doors per train side, two axle outboard bearing fabricated steel truck, 145 ' minimum horizontal curve radius, +/- 2500 ' minimum vertical curve radius, 600 v DC third rail power.

Passenger capacity is 57,600 pphpd with a two-minute headway and 28,800 pphpd with a four-minute headway.

MONTREAL RUBBER TIRED HEAVY RAIL CAR (1974 DELIVERY)

This design used a married triplet with an ABA arrangement. Three of these were used per train to provide a nine-car train. The A cars have an operator's cab and are fully motorized. The B car has neither. The car length averages about 55'. A rubber tire design is used that has 4 support tires and 4 lateral guidance tires per truck. There is also a steel wheel arrangement on each truck. The following parameters are based on the nine-car train.

Train length 555', width 8' 3", height 12', empty weight 490,500 lbs., maximum service speed 45 mph, 360 seats, 1080 standees, boarding level 47", 36 doors per train side, unique fabricated truck design, minimum horizontal curve radius of 150', max grade 6.5 %, third rail power collection.

Passenger capacity is 43,200 pphpd with a two-minute headway and 21,600 pphpd with a four-minute headway.

2. Advancements in Deployed Technologies

INTRODUCTION

This chapter reviews technologies that are in development or are not in widespread use in the US. With one exception (low-speed Maglev), the items listed in this chapter are not new vehicle technologies, but technology advancements that may extend the functionality of existing vehicle technologies. For longer range planning they can be considered, however, not all of these concepts may become viable products.

BUS ADVANCEMENTS

Bus systems will always be a vital part of transportation systems as they satisfy the large demand for serving relatively low passenger density routes. This concept also requires the lowest investment and shortest time to begin service on new routes. Therefore, considerable effort continues to enhance the design features of this technology. However, the lack of entrainment when using this concept limits its passenger capacity. Claims to the contrary should be carefully reviewed with regard to bus application factors, such as, seats available, standing passenger density, bus length, and practical headway assumptions.

Civis

Bus average speed is significantly improved if an isolated guideway is used, similar to that now used in Pittsburgh. Apparently to improve this concept the guided bus design is being offered, such as the Civis concept. However, the cost-benefit relationship for this concept appears questionable, as the only advantage other than the marketing appeal appears to be a slightly narrower guideway, which may not be safe if the driver has to operate the vehicle when the automatic steering system malfunctions.

Tram-on-Tires

In Europe, many people in industrial countries, such as France, Germany, England, etc. recognize the value of light rail transit. However, politicians and planners properly express concern regarding the cost of LRT. In an apparent attempt to solve this "problem" designs are being offered that appear to be LRT but are actually a bus. The Bombardier designed Tram-on-Tires is an example that has been ordered by the transport system in Nancy, France. This design is a trolley bus that uses a street mounted guidance rail. The design can also be dual powered with the addition of an internal engine. While technical details are not available, there are apparent questions. The force levels required to guide an approximately 55,000 pound rubber tired vehicle using a single guidance rail can be expected to be quite high. How is the guideway repaired? The guideway concept eliminates the flexibility advantage of the trolley bus concept. The maximum speed is shown as 44 mph. With a driver used for this concept its technical and cost advantages are not apparent. Again, aside from the marketing appeal, it appears that a double articulated trolley bus would provide the same functions.

Fuel Cell

The fuel cell is the power source of the future. The key question is: when will it be cost competitive, and how cost competitive must it be when its emission reductions are considered and quantified? Fuel cell development for transportation has been active for many years. Recent US Government initiatives are further expediting development work. Many major companies are very active, for the potential large markets of private autos and stationary power. This work will significantly reduce the fuel cell cost, as it will expedite the learning curve cost reduction that has occurred for all new technologies. SunLine Transit in Thousand Palms, California has been a major testing ground for reduced emission bus testing. They have tested a fuel cell powered bus using a New Flyer H40LF. An additional concern for fuel cell operation is the source and safety of the hydrogen fuel. CNG buses have similar concerns that have been overcome. An on-board hydrogen generator that uses Methonal may be an answer.

STREAM

The trolley bus is an excellent concept, having good performance and operating flexibility. However, its overhead power system is unsightly, especially at intersections. If a separate guideway is used would this issue still be a problem? In an effort to solve this problem for normal street operation, a street located power distribution system, STREAM, is being developed. It is designed to supply power only at the actual location of the moving bus, by using a mechanical or electronic switching system, that also senses the bus location. It is being developed by an Italian Transportation Company, Ansaldo-Breda, with the first commercial trial in Trieste, Italy. Operating information is not yet available. Apparent concerns are the complexity and safety of the power switching system, and the repair cost when failures occur in the street located switching system. Cost information is not yet available to permit a comparison with a standard trolley bus overhead wire system.

LIGHT RAIL ADVANCEMENTS

STREAM

The STREAM concept can also be used to deliver power to light rail vehicles, replacing the need for a catenary system.

LOW-SPEED MAGLEV ADVANCEMENTS

There are at least two major programs for developing low speed Maglev transportation systems. The TEA-21 funding created FTA development projects, and the Japanese HSST program plans a new system by 2005. US cities also continue to evaluate Maglev possibilities, such as Pittsburgh with a private development company.

FTA funding began in 1999. A contract was awarded to General Atomics Corp. Four other companies are now also working on similar projects to develop viable Maglev technology. The present work should be completed in the second half of 2003. It includes system studies, technology risks and resolutions, and technology recommendations. The second phase will include subsystem development and testing. The third phase will include system integration and deployment planning. Funding is from the US FHWA. Technology changes for low speed operation are not known, except that more use of permanent magnets is expected. To date the approved funding has been at low levels.

The Japanese Chuba HSST Development Corp. has been developing Maglev technology since 1974. Their plans include providing a 6-mile Maglev line for operation from an existing subway station to connect to the 2005 World Exposition, at Toyota City. Their HSST technology appears better suited to low speed operation, because it uses the active vehicle concept that greatly simplifies the design and cost of the wayside power distribution system. In an active system, the propulsion is provided within the vehicle. The propulsion system uses the linear induction motor concept, similar to the Bombardier Skytrain. However, Maglev technology can control and minimize the linear induction motor air gap between the vehicle and the track located reaction rail, and therefore improve the linear motor efficiency.

Low speed Maglev permits the use of an active vehicle instead of a passive vehicle. This factor significantly reduces system life cycle cost. The Maglev concept was developed to provide very high-speed ground transportation. The advantage of using it at low speed requires a site-specific analysis that accurately evaluates the total cost of its operation, versus conventional wheel/rail technology. Assuming equivalent vehicle passenger capacity, structural strength, operating speed, guideway curvatures, and safety, both technologies can be properly compared. The key issues to compare are the wheel/rail maintenance and energy requirements of conventional technology, versus the reliability, energy requirements, and installation cost of Maglev.

For low speed operation speed is no longer an issue, only farebox recovery dominates. The system design should utilize the speed capability of the specific maglev design being considered. If stations are too close the max speeds may not be reached. Acceleration and deceleration should not significantly affect this as max values should be limited to standard values as required by passenger comfort. Above all, the key issue is the required average and maximum speed requirements to obtain the desired run times. Life cycle cost is related to an exponential function of speed.

DIESEL MULTIPLE UNIT (DMU) ADVANCEMENTS

FRA Compliant DMU Car

The new Diesel Multiple Unit (DMU) cars being offered by European suppliers do not meet the FRA collision design standards, similar to LRV designs, because they are designed to the European standard of 150 metric tonnes of car body compression load. Therefore, they must be separated by time from operating with the stronger FRA compliant designs. If the service is isolated from railroad service, the FRA requirement is not applicable, however, planners should be aware of designs that have been proposed by at least two major car suppliers that will meet the FRA standards. Both designs are based on operating, self-powered, Electric Multiple Unit (EMU) designs.

Bombardier has offered a design based on the EMU car now being used on the Two Mountain Line commuter service in Montreal. Nippon Sharyo has offered a design based on the EMU car used by Northern Indiana Commuter. The two designs are similar in that they both have two propulsion diesel engines, high-level floor, 85' in length, and two end doors per side. The other parameters are given for the proposed Bombardier design. They are: 85' length, 10' 6" width, 12' 11" height, empty weight of 127,500 lbs., 100 mph operating speed, up to 92 seated passengers, 250' horizontal curve limit, 2000' vertical curve limit.

The passenger capacity is 11040 pphpd with 2-minute headways, and 5520 pphpd with 4 minutes headways. However, these headways are much shorter than typically used in their intended commuter service.

Conventional DMU

The DMU design recently sold in the US uses the modular design. Conventional designs, that are similar to a conventional LRV mechanical design, are also available. An example is the Siemens DESIRO Class 642 used by German Rail. This design is single articulated, with a 275 kW propulsion engine on both cars. Empty weight is 159,000 lbs. Top speed is 75 mph. 123 seats are provided. It should be noted that not all DESIRO designs are a DMU, as Siemens uses this design platform for several design concepts, including EMU's. Note that the Siemens RegioSprinter is no longer available.

COMMUTER/INTERCITY RAIL ADVANCEMENTS

Gas-Turbine Locomotive

This FRA-Bombardier locomotive development has been successfully tested at Pueblo. A countrywide demonstration planned initially for Summer of 2002 has been delayed while FRA and Bombardier come to agreement on the passenger cars to be used. Spare Acela cars were originally planned, however, Amtrak now requires these cars for revenue use.

This internally powered locomotive design provides the high horsepower that is required to operate commuter and intercity trains at higher speeds without the need for route electrification. Turbine powered locomotives and cars are not new in the US. The Union Pacific RR operated a fleet of 4500 and 8500 hp designs about 40 years ago. An electric multiple unit (EMU) was converted to turbine power for the Long Island Railroad. Turbine power can also reduce the locomotive weight, a benefit for passenger service. The key issues have not changed, fuel consumption at partial load, and turbine blade life as limited by dirt erosion.

Tilting Cars

This concept has been in use for many years. It has been more frequently used lately as train speeds are increasing. Bombardier has provided an active system for the Acela train. The Fiat active system has been used on many car designs in Europe. The Talgo train is the only design using a passive design, with the car tilting naturally due to pendulum action. This concept will increase the train speed allowable on curves as it tilts the car to compensate for lateral force on the passenger when operating in curves. Tilting should be considered for longer haul service if the route has significant curved track mileage.

3. Corridor Considerations

INTRODUCTION

There are many factors to consider when selecting an optimum passenger transportation system design. The prospective passengers want a comfortable, prompt, seamless trip and often have the alternative of using an automobile if it does not meet their expectations. The operating agency wants a reliable system with the flexibility to grow to meet the needs of route extensions and increased ridership. The supporting government agencies want a low operating cost to minimize the fairbox subsidy. The planning and selection process is often complicated by conflicts that arise between the many project objectives.

To determine technology requirements of a specific corridor transit application, many factors should be considered that can be defined by the following four major issues, which are discussed in more detail later in this chapter:

- The **integration of transportation modes** in the total transit system, with the relationships of low, medium, and high passenger density routes defined.
- The required **corridor-specific performance**, such as, the peak one-hour passenger capacity, the maximum allowable running time between endpoints, and the need to share a right-of-way with other users or to make crossings at grade.
- The **physical conditions** of the route, such as, operating level (street level, elevated, or underground), and route conditions (grades, curves, weight limits, and speed restrictions).
- The **life-cycle-cost** of the system procurement and operations (especially vehicles), the compatibility of different technologies that must coexist in the transit system, and the risk of using new or unique technology.

In addition to engineering considerations that can be expressed as requirements, the public and their elected officials may also have preferences that can influence the selection of technology. Styling issues or advanced features may reinforce the community's self-identity or to make a proposed system more appealing. Some technologies may be perceived as cleaner, quieter, less obtrusive or more advanced. In the technology selection process, preferences and engineering requirements often are considered together, but only when other technical and economic requirements will also be satisfied. While the public may support a technology based on its appearance or image, their support will deteriorate if reliability and operating subsidies are not satisfactory.

During the selection process, iterations will be required due to conflicts that arise between satisfying the many issues. In addition, for some technologies it may be difficult to obtain operating cost information or maintenance cost information. This can often be resolved by requesting information from transit agencies that use similar technology. However, when using this information, any significant operating differences between the source and the actual route being studied should be noted, for possible modifications of the information.

This chapter addresses the four major issues described above in turn, and then discusses the incremental nature of the technology decision-making process and the evaluation and management of risk when considering new technologies.

INTEGRATION OF TRANSPORTATION MODES

Discussion

A metropolitan transportation system will require multiple transportation modes to serve its many routes, with several different passenger capacities typically required to serve the public needs. When studying a specific route, its "fit" into the overall transportation network should be reviewed, with long-term passenger travel growth also considered. For example, a bus system may "feed" an LRV system that may feed a heavy rail system. Any of these systems can also connect with special activity modes, such as, shuttles, city circulators, and airport circulators to distribute passengers locally, or with long distance services, such as, commuter rail and high speed rail.

Each of these modes has different requirements for key items, such as, station design, distance between stations, acceptable waiting time for passenger pickup, acceptable travel time, required seating, convenient transfer between modes, power level, and guideway clearances. Requirements for passenger safety, fare box recovery ratio, equipment reliability, and future growth capabilities are common to all public transportation modes. Each mode can satisfy these requirements if it can provide the service level that is required at a competitive cost. The capital cost and the operating cost should both be analyzed to ensure a satisfactory life-cycle-cost for the selected technology.

Integration of transportation modes in a total transit system is often difficult, because there may not be a predetermined system architecture to "fit" with. Every time new major investments are considered, system-level issues may be reconsidered. Some questions that rise during system planning include:

- How much transferring is acceptable, as opposed to direct one-seat point-to-point service?
- Which users should be made to transfer and which should have a direct trip?
- What system design will make the transit system become easier to understand and use?
- Is there a benefit to standardizing modes to reduce maintenance costs?
- Are there system-wide goals for speeds, headways, travel times and seat availability?
- Will the planned mix of services match local and regional travel needs?
- What capacity will be needed in critical segments over the long run?

System Integration Evaluation Measures

These measures assess how well the candidate technology fits with the architecture of the total transit system, whether it makes good use of common infrastructure, and whether it can accommodate policy needs of the implementation agency.

- *Fit with system architecture.* How well does this technology fit the system-level architecture of the transit system? Is the level of transferring acceptable, and can transfers be accomplished easily? Will there be an effect on the total system capacity if this technology is chosen, once the full system is completed? Will the technology meet any established performance guidelines?

- *Use of existing infrastructure investment.* Will the technology require investment in maintenance equipment, inventory, or specialized expertise that would not be required for a different technology that could use existing infrastructure instead?

- *Policies and Preferences.* Will this technology accommodate the passenger experience desired by the implementing agency? Are there important differences in how well it will accommodate policy needs to be defined by the agency, such as fare collection, accessibility, security, passenger information, etc?

CORRIDOR-SPECIFIC PERFORMANCE

Discussion

Satisfactory performance in a specific corridor will be defined by the route characteristics, such as, length, travel time expectation, acceptable platform waiting time, platform length restrictions, intermediate station stops, and transfers to other routes. During a corridor planning study, transit alternatives with varying route characteristics are evaluated using a broad set of performance measures to determine which alternative best meets the technical requirements for transit performance and capacity, while meeting other community objectives and minimizing costs and environmental impacts. A review of the following issues will identify technologies that can provide satisfactory performance.

ROUTE CAPACITY

The route passenger capacity of a given technology, in people per hour per direction, is the accepted method for showing the capacity of a technology. Once the basic performance needs of a route have been established, the actual passenger capacity is easily calculated by multiplying the bus or train capacity by the maximum number of trips per hour that can be operated, considering the system design capability for providing this headway in a safe manner. Claims for capacity by vendors or proponents are sometimes exaggerated, and should be examined critically.

Bus or train capacity is based on the selected vehicle, the required seating arrangement, and the number of cars per train. A longer car makes better use of train length, with dead spaces between cars being minimized. Smaller cars are favored when a rubber-tired system is used, to reduce weight and obtain satisfactory tire life. A busy airport people mover uses short trains with short headways such as 90 to 120 seconds. A commuter service may be satisfactory with 30-minute headways, as long as schedules are met. With a car passenger capacity of 100 people, four cars used per train, and a three-minute duration between trains (headway), the route capacity is 100 x 4 x 60/3 = 8000 pphpd.

VEHICLE HEADWAY (SPACING)

The route signaling system is designed to safely separate trains following each other. A fundamental design parameter is the stopping distance of the vehicle. As this is an energy-related issue, the weight and speed of the vehicle are the key parameters that define the available stopping distance.

For example, assuming a typical deceleration (braking rate) rate of 3 miles per hour per second, a people mover operating at 24 mph will require about 150 feet to stop. At the other extreme, a train operating at 175 mph may require three miles to stop. If headway is only limited by vehicle speed, headway must increase as vehicle operating speed increases because the vehicle braking distance increases with increasing speed. For a given train design, the maximum passenger line capacity will occur at a relatively low speed. Therefore, before specifying actual line capacity, operating speed and signal system design capability should be defined.

For capacity estimating purposes a headway can typically be selected, and assumed to be available, if it is a typical level of two to four minutes or longer. Note that train speed is generally not a consideration at this point. Train headway is selected to satisfy the passenger and to obtain the needed passenger capacity. A shorter headway requires more vehicles in operation and a related higher energy use. A longer headway will increase the required passenger capacity per train and reduce the required quantity of trains, if platform length restrictions are not limiting.

AVERAGE SPEED

Average vehicle speed is a key component of passenger satisfaction and system scheduling. A higher operating speed can increase route ridership. However, a higher top speed will result in higher energy cost and higher vehicle and guideway maintenance costs. The selection of the optimum average speed is an important decision. The average route speed is dependent on several factors, such as maximum train acceleration and deceleration, number of intermediate stops and their required dwell times, maximum route speed, route civil speed restrictions, grades, interaction with traffic in a shared right-of-way, and possibly passenger loading (train weight). A brief review of each of these items follows.

Train acceleration is typically provided at 3 miles per hour per second, as it is the maximum value used as limited by passenger comfort. However, a key variable, that is typically not shown, is the maximum speed at which full acceleration is available. A vehicle performance curve (speed vs. tractive effort) typically has a constant tractive effort segment, which at a design speed becomes a constant horsepower segment. The higher the speed of this changeover point, the higher the average speed can be, and the higher the energy use will be. For vehicle concepts that do not have all axles powered, such as a DMU car, or that use locomotive hauled technology, the vehicle speed vs. tractive effort curve will provide much lower initial acceleration and lower horsepower, and therefore a lower average speed for the same route conditions.

By properly managing train speed, energy use can be reduced. If a train accelerates to top speed, but only operates at that speed for a short interval before speed must be reduced, a lesser top speed should be used. This issue, as well as overall train performance capability, should be analyzed using a computer based train simulation program. When a final train analysis is performed, unusual operating conditions should also be considered, such as, dead cars (inoperative) in a train, low traction supply voltage, and extreme passenger loading (special events). A few vehicle technologies have a "load weighing" function that increases vehicle tractive effort as passenger load increase to maintain a constant acceleration. However, this function may only provide this feature at a limited passenger load, with a resulting performance decrease at the highest passenger load.

Train deceleration is also typically provided at 3 mphps. However, a lower value should be considered. A wheel slide can occur and damage a steel wheel if rail conditions cannot provide the adhesion (friction coefficient between the wheel and rail) that the braking rate requires. To safely operate an LRV in city traffic it is equipped with "track brakes" (steel shoes that clamp directly to the running rail) that increase the vehicle braking rate to 6 mphps for emergency stopping. A vehicle braking system may use several subsystems, such as, electric resistor braking (dynamic braking), regenerative electric braking, wheel tread mechanical braking and axle disk mechanical braking, with all being power limited. When studying a train application, the total vehicle braking effort reduction due to a possible failure of any of these braking subsystems must be considered.

Each train technology is designed to operate at a top speed, with several technologies sharing an operating speed range. An operating speed is typically lower than the vehicle design speed. Small people movers typically operate in the speed range of 15 to 30 mph. Larger rubber tired vehicles, such as Innovia, VAL , and monorails typically operate in the speed range of 35 to 45 mph. An LRV has typically operated in the 40 to 50 mph range, if not restricted by street traffic. Newer designs are expected to operate at about 60 mph. Conventional commuter trains operate in the 70 to 120 mph range, if train horsepower and proper signaling are used at the higher speeds, and grade crossing protection is satisfactory. High Speed trains operate in the 125 to 175 mph range, with wayside conditions being a limiting factor. Higher speeds are planned and are now being tested.

Maglev is a concept that is designed to achieve very high speeds, such as 300 to 350 mph. These speed ranges should be considered as general information. While each vehicle specification will show a top speed, and perhaps a suggested operating speed, a major consideration is ride quality, that is not specified. While this is a complex issue that is related to car interior vibration amplitudes, frequencies and duration, it can easily be "measured " by riding the vehicle in question over its suggested operating speed range.

At the planning stage it is most important to note that the design of the system will more often limit the performance of a transit service than will the technology. Station spacing and interaction with other traffic sharing the right-of-way are usually limiting factors to performance, rather than engineering capabilities of the technology applied. In some cases, transit priority measures can be applied to partially mitigate for such performance limitations.

Corridor-Specific Performance Evaluation Measures

These measures assess how well the candidate technology fits the service requirements for the application:

- *Match between capacity and forecast demand.* How appropriate is the capacity provided by the technology for the level of demand forecasted in the corridor over the planning horizon and the expected life of the investment? Can capacity be expanded in the future if needed? Could another technology provide the needed capacity at less cost?
- *Suitability of the technology to the service.* Is this technology the best fit for the desired service pattern, including desired headways, stop spacing and line distance? How suitable is this technology to the desired operation plan, including the ability to skip stops in express operation, to pass a disabled vehicle, or to accommodate branch operation? Are high levels of service desired at all times of day, requiring automated operation in order to be cost-effective?
- *Suitability of the technology to the right-of-way.* Is it desirable to share right-of-way with other vehicles, either railroad or automobile traffic? Is it desirable for vehicles to be able to leave the guideway to operate on local streets?
- *Connecting services or future extensions.* Will this service connect directly to an existing service, or be extended into the future? If it may be extended, will the measures above apply equally to the full line once extended?

PHYSICAL CONDITIONS

Discussion

The physical, or Civil Engineering related, route conditions are a major factor when selecting a satisfactory vehicle technology. Only general comments are provided because this is a complex issue. In fact, route conditions may override other considerations for selecting a satisfactory vehicle technology, or the requirements to implement a predetermined technology may effect the selection of a route and horizontal and vertical alignments.

CLEARANCE

If the route is to be underground, a minimum clearance envelope is attractive for reducing construction cost. Guideway technologies are preferable to manually steered buses for long tunnel segments.

An optimum low to medium capacity system could use a people mover system with small cars and a short headway. The Bombardier "Skytrain" would provide a higher speed, higher capacity, small clearance system. A heavy rail system will require a larger clearance envelope, however, only it can provide a very high passenger capacity. These systems use a traction power supply contact system that is in close proximity to the guideway/track. The high vertical dimension required by an LRV, due to its use of an overhead wire power supply, is not as attractive for this service. Similarly, the high vertical dimension required by a typical monorail vehicle and its guideway is not attractive. Of course, diesel engine powered vehicles are not acceptable due to their exhaust, unless the tunnel section can be equipped with an external power source, and the vehicle designed for dual-power operation.

The minimum required horizontal and vertical curves must be reviewed to determine if the desired vehicle technology has a compatible design capability. The dynamic clearance envelope of the selected vehicle must be carefully reviewed, also considering car component failure modes, before final system design is completed. Fire safety and passenger evacuation must also be reviewed.

If an elevated guideway is required, lightweight and minimum visual impact are desired features. However, train emergency passenger evacuation and walkways may need to be provided by the guideway/track design. Also, switching between tracks should be provided for maintenance and emergency conditions, which may require operation that bypasses a station or a track section. Above all, the vehicle and its guideway must be able to provide the required passenger capacity. Various technologies show a very wide range of projected cost per mile. This issue should be closely examined, with the above considerations included, before a guideway cost estimate is accepted.

If city street operation is planned, only an overhead power collection system is now viable. If the selected route is separated from all others, and does not have a clearance restriction, any form of power collection can be used.

GRADES

Grades should be minimized in all cases to reduce energy cost and increase average speed. Grade operation increases the duty on the vehicle traction system, therefore the length and the grade must both be considered to determine if a specific vehicle can operate on the required grades of a route. A rubber-tired vehicle can typically operate on a steeper grade than a steel wheel vehicle. The use of rail sanding will also improve grade operation. An LRV has this feature and can routinely operate on 5% grades with peaks at 9%. A rubber-tired vehicle can generally operate on grades that are twice as steep depending on the peak and sustained capability of the propulsion system. Guideway/track conditions, such as dirt, oil, water, and ice will significantly reduce the maximum negotiable grade operation.

The transition between level operation and grade operation requires a vertical curve. Vehicle vertical curve capability varies considerable for various vehicle technologies and should be reviewed during system planning. If locomotive hauled service is being considered, grade becomes even more important, because the available locomotive tractive effort must increase as the grade increase. For example, train operation on level track requires about 5 pounds of locomotive tractive effort for every ton of train weight. If the grade is increased to only 1%, this value increases to 25 pounds of tractive effort per ton of train weight.

WEIGHT

Train weight is a major factor in guideway/track design. In addition to total train weight, the issues of peak wheel vertical loading, both static and dynamic, and lateral guidance loading must be considered. On structures, the weight of the guideway itself may also be an issue. The peak train weight will typically occur during special events, such as concerts or sports, as train length may be increased, and passenger crush loading may exceed normal values. Design crush passenger loading is typically at 4 people per square meter. However, the guideway design should have the capability of at least twice that.

A review of vehicle weight per length of train, or per passenger, will provide confusing information due to the different structural designs that are used for the various vehicle technologies. Weight is also impacted by the longitudinal strength of the car shell and its "crashworthiness". For example, the Acela train weight is about 45% heavier than a similar design would be for European service. Crashworthiness design standards only exist for commuter cars in FRA regulated service. This concept uses crumple zones to partially absorb the collision energy, as well as structural specifications. A people mover will typically use a lightweight car shell structure with a fiberglass overlay or panels. A conventional rail car will use undercar beams to provide longitudinal strength. While there is not a "right" answer for vehicle strength, if only one design concept is operating on a route, the differences in vehicle structural designs and their impact on vehicle weight should be understood and fairly evaluated.

ROUTE CURVATURE

The required route curvature can eliminate specific vehicle technologies. If fixed guideway operation is required on the tight curves of a city corner, an LRV is a good choice, as it typically has the capability to operate on an 85' radius curve with designs in service operating on a 45' radius curve (San Francisco). Other vehicle technologies with a minimum turning radius capability in the range of 40 to 85 feet radius are; 100 % low floor LRV (Combino), Innovia people mover, and proposed small PRT vehicles. In the range of 110' to 140' minimum curvatures, the small modular DMU and the Bombardier Skytrain can be considered. Monorail vehicles can operate with minimum curves in the range of 150' to 200' Locomotive hauled and FRA compliant DMU cars (both 85' length) require a minimum radius of 250' to 300'.

PLATFORM DESIGN

Platform design can vary from a simple concrete slab used for a commuter rail stop, to a complex multilevel underground high loading platform of 400 feet in length, with escalators, elevators, and a traction substation also included. Passenger capacity is again the key factor, with the peak flow of incoming and exiting passengers to be considered. Station design must consider the ADA regulations that define the boarding requirements for disabled passengers. Buses and LRV's can provide high or low level boarding, or both. If needed, a bridging plate is used to eliminate the vertical and horizontal gaps between the car floor and the platform.

Commuter trains can operate with high and low level boarding, with stairs provided for low level and vestibule plates used for high loading. ADA compatibility can be provided with car mounted lifts, wayside lifts, and minihigh wayside ramps. Rubber tired fixed guideway vehicles typically use high-level platform passenger boarding. The quantity, location, and width of the train side doors impacts passenger flow and should be considered during platform design.

Physical Conditions Evaluation Measures

Evaluation measures for physical conditions assess the suitability of the technology to the physical conditions addressed above. The measures are most likely to come into play when the right-of-way has been predetermined; otherwise the right-of-way will more likely be designed to meet the requirements imposed by the preferred technology.

Measures assess whether the technology can meet design requirements for:

- *Vertical and horizontal clearances and curves.*
- *Grades.*
- *Acceleration and deceleration.*
- *Live and dead load on structures.*
- *Platform design.*

LIFE-CYCLE COST

Discussion

This is one of the most important issues for evaluating vehicle technology, yet, it is the most difficult to quantify. The factors are first cost (construction, procurement of vehicles and systems, and startup), operating cost, and maintenance cost. A brief review of key issues follows.

FIRST COST (CONSTRUCTION, PROCUREMENT AND STARTUP COSTS)

Regardless of the technology selected, guideway location (at grade, elevated or subway) will have a major cost impact. If street operation is required, only a few technologies are acceptable. Therefore, the selection of a technology that requires a separate, protected right-of-way may require relatively expensive elevated or underground segments.

The cost of procurement of vehicles and systems, as well as startup costs, will depend on the experience of the many suppliers, and the total quantity of each subsystem that has been produced by the suppliers. By using an existing vehicle design, with minimum changes, vehicle price will decrease. If the design is in current production, especially in large quantity, a further price reduction can be expected. If subsystem components from a large quantity order, such as New York City Transit cars, can be used their prices will be very competitive. If the vehicle can be purchased from several competitive suppliers, bidding competition will result in a lower price.

Several vehicle technologies meet the above requirements to varying degrees, such as, unpowered commuter cars, light rail vehicles, diesel-electric locomotives, and buses. However, there are many vehicle technologies that use a unique vehicle and/or guideway design that can result in a higher cost initially and for future route extensions. Each rubber tired fixed guideway vehicle design and its corresponding guideway design are different than all other suppliers of this concept. This is also true for monorail designs. The Skytrain design uses a unique double power rail design. Maglev is very special with radically different designs used by the German and Japanese systems. Maglev requires a very extensive power distribution system, with the vehicle using the passive design concept that is used to control the speed of each vehicle independently. Every car operating on a system requires its own power supply input, that changes with vehicle location. The future availability of a unique design is also a vital issue that should be considered, as technology always changes with time.

In summary, the purchase of a unique design should be carefully considered, if a more conventional design is satisfactory. If the planned route will not be extended, and if sufficient spare parts are purchased with the original order, the risk of using a unique system can be minimized.

The traction power cost should also be reviewed, with several designs used that depend on the vehicle technology selected. Substation size and spacing also vary with vehicle technology. Traction power distribution lines can be located at the wayside, in the guideway, or overhead with support poles typically used.

OPERATING COST

The two key factors are operating personnel and energy cost. Vehicles that operate on physically isolated guideways often use an automatic control system without a driver. Automatic operation may be required to provide short operating headways. Automatic operation also allows a higher service frequency during off-peak periods than would generally be provided when an operator is needed on each train. However, if driver elimination is the reason for selecting automatic operation, the cost saving of eliminating the driver should be compared with the cost of the personnel needed to attend and maintain the automation equipment, and the desire to maintain an operating staff presence on trains and at stations for security and customer assistance purposes.

Energy and power demand costs depend on vehicle weight, top speed, number of stops, and passenger load. A secondary, but important factor, is the efficiency of the propulsion system. Vehicles driven by rotary motors have similar efficiencies, whether DC or AC traction motors are used. When linear motor versions of induction motors are used the motor efficiency can be 25% lower, due to the large motor air gap that must be used as a result of the linear motor reaction rail to vehicle tolerances.

MAINTENANCE COST

The two basic categories are scheduled and unscheduled (failure) maintenance. The scheduled servicing requirements for the many vehicle subsystems may require different time intervals. Car overhaul intervals should consider these needs. Unscheduled maintenance will depend on the reliability of the subsystem components, therefore, all should be service proven. If new technology is used, the associated risks should be investigated. To investigate this further, a representative vehicle maintenance schedule can be obtained from potential suppliers.

Routine servicing cost will depend on the requirements of the subsystem components. This can be evaluated by reviewing supplier's maintenance recommendations for items such as; lubrication, filter change, brush replacement, wear allowances, cleaning, adjustments, etc. The wheel drive arrangement should be reviewed to determine the acceptable operating difference that is permitted between wheel diameters for both steel and rubber designs. The allowed difference will determine the required interval between turning steel wheels or replacing rubber tires.

The service life of vehicles and preservation needs for civil facilities should be factored into life-cycle cost calculations.

Life Cycle Cost Evaluation Measures

Evaluation measures for cost associated with technology choice include:

- *Right-of-way costs associated with the technology.* Are there differences in the cost of preparing the right-of-way that are attributable to the technology rather than to the service pattern? For example, would the technology choice result in additional structures or tunnels, wider right-of-way or strengthening to bear a heavier load?
- *Construction, procurement and initiation costs.* Not including cost of preparing the right-of-way.
- *Operating costs.* Includes cost associated with operating and supervising vehicles, maintaining tracks and related systems, and staffing stations.
- *Maintenance and preservation costs.* If applicable, includes added expense of maintaining separate spare inventories and hiring specialized expertise when implementing multiple technologies.
- *Life-cycle costs.* This measure includes all costs shown above, and also factors in the expected life of different system components, including depreciation or replacement needs. It is calculated over the life of the facility (or a set time period) and expressed as an annualized cost.

TECHNOLOGY SELECTION DECISION-MAKING PROCESS

In most cases, the selection of a transit technology occurs incrementally over a period of years, as plans for a transit investment progress from an initial proposal through a corridor planning process, and then into design, construction and procurement. Early in the process, the exact technology is not as important as are generalized service requirements. Once design and procurement begin, then it becomes critical to specify a technology and its associated design requirements. Different information is known at different points in the process, and different decisions need to be made at each step.

PLANNING STAGE - CORRIDOR ALTERNATIVES ANALYSIS

A corridor planning process may be initiated when a corridor has been identified where a major investment may be warranted. During the corridor planning process, alternative transit services are defined and evaluated against one another, considering factors such as the ridership attracted to the service, the cost of constructing and operating each alternative, public input and environmental impacts. Often a generic technology is assumed as part of each alternative, but the emphasis is on distinguishing the differences between alternatives that will deliver functionally different service to potential users.

Service characteristics, such as whether vehicles can leave the guideway (like buses), whether the service will operate in mixed traffic or be fully grade separated, how far apart the stations will be, and how far the service will extend determine the conceptual cost and the passenger demand associated with each alternative. A limited set of technology options will be suitable for each alternative, but selection of a specific technology may not be made until more detailed information is available during the design or procurement process. For extension of an existing service, the connecting service may define the technology selection, and the service characteristics must then be constrained so as to be consistent with the capabilities of the pre-selected technology.

To compare alternatives, service is defined and modeled, including general routes, alignments and station locations. To determine the cost and effectiveness of different alternatives, demand modeling is used to determine likely ridership, and conceptual engineering is needed to determine where a transit alternative will be placed at-grade, on an aerial structure or in a tunnel. Capital and operating costs (or cost savings) are calculated, including for existing transit services that would be rerouted to provide feeder service, or that would be eliminated due to duplication with the new service.

At the planning stage, the range of technologies to be considered further may be reduced, but the final technology selection may not be needed. Each technology mentioned in this report has been developed to be especially well suited to specific applications. For any given application, only a few technologies are an appropriate match. Some technologies are more flexible than others or can be customized to meet a variety of application needs, while others are suitable only for a small subset of specialized applications. Rather than to examine every technology in great detail at the planning stage, it makes sense to narrow the field to the most suitable matches for the application, and then to examine those that remain more thoroughly.

Service requirements that may limit the range of applicable technologies at the planning stage include the following:

- *Need to share right-of-way or cross at grade.* To be able to operate in mixed traffic, only buses and light rail can be considered. If it is desirable to combine feeder and linehaul service to reduce transferring, light-rail and bus technologies are required, since a portion of the trip will require use of shared street right-of-way. Only buses can operate in freeway HOV lanes, and only commuter rail technologies can be used on existing railroad-owned track.

- *Ridership capacities to be accommodated.* The anticipated capacity needs over the life of the investment may narrow the range of applicable technologies. For example, if greater than 30,000 passengers per hour per direction are anticipated, only heavy rail is suitable, since longer train lengths (up to 10 cars) short headways, and high acceleration and deceleration can be achieved.

- *Guideway location (grade, elevated, underground):* In general, tunnel costs increase exponentially in proportion to the radius of the tunnel, so if extensive elevated or tunnel sections are required, buses become less competitive due to their increased right-of-way requirements. Guided buses may reduce this cost in theory, but this application has not been proven in service. Lower profile fixed guideway vehicles will also reduce tunneling cost. (Detailed analysis is required to choose the best technology for a specific tunnel or elevated application.)

- *Limited R/W Width:* Buses require a 20 ft. right-of-way per direction to allow a disabled bus to be passed by another vehicle. Any fixed guideway technology will fit a smaller right-of-way; for very tight clearances more detailed analysis is required. Buses equipped with mechanical or electronic guidance can be operated in a constrained right-of-way, but the guided busway must be separated from other traffic, and special attention is required to clear disabled vehicles from the guideway.

- *Steep Grades:* Rubber-tired vehicles generally can climb grades twice as high as steel-rail vehicles, but specifications vary greatly depending on the peak and sustained capability of the propulsion system. Trolleybuses can accelerate and maintain speed on steeper hills than conventional diesel buses. Standard monorail equipment is specified for approximately the same grades as light rail vehicles.

- _Route length and complexity_: For fixed guideway systems, longer routes and more complex rail networks require greater ability to reroute trains to operate around disabled trains or to skip stations in express operation. While all transit technologies can accommodate switching, as the number of required switched increases, systems requiring specialized or proprietary switches, control systems and other system components may become less competitive compared to more standardized systems. If point-to-point dynamic routing is desired, only PRT is applicable, and only for collection and distribution within a local area. PRT may be appropriate for circulation within an activity center, or to collect and distribute passengers in the vicinity of a transit station.

- _Level Loading_: Any fixed guideway technology can be specified to accommodate platform-level boarding. Buses can be specified to achieve level boarding, but a bridging plate may be needed to traverse the gap between the bus and the platform, and low-level doors must also be provided if the bus will make stops at traditional bus stops. Additional doors will reduce the seating area.

- _Low Operation Cost (or higher off-peak frequency)_: Operating labor is the biggest component of transit operating costs. Automation can reduce operating costs because a driver is not required, and it can reduce the incremental cost of maintaining frequent service during off-peak periods. However, many automated systems continue to deploy operating personnel along the route to inspect fare compliance, provide security and attend to customer care. If automation is required, only guideways that are completely separated from traffic and pedestrians can be considered. Larger capacity vehicles and trains can be operated at reduced frequencies to reduce operator requirements. For example, articulated buses can serve the same passenger load with longer headways than standard coaches.

IMPLEMENTATION STAGE - DESIGN AND PROCUREMENT

When a transit alternative has been selected and implementation begins, vehicle specifications need to be known in order to determine the exact engineering requirements that the facilities will be designed to meet. During the vehicle and systems procurement process, any custom specifications need to be identified, and a vendor is selected. Detailed engineering analysis is required to determine the best technology match for a specific application.

The final selection of an optimum vehicle technology should consider the factors discussed in this chapter above. Some factors are relatively simple, such as establishing the route passenger capacity requirement and its necessary average speed. However, the growth in the passenger capacity requirement can be difficult to evaluate, therefore the required future route capacity should be estimated to determine if, and how, the capacity can be increased when needed. Future route expansions may result in the need for vehicles that can operate on several routes, therefore future vehicle/guideway compatibility should be considered. A passenger acceptable headway is also a vital factor, as it affects signal system design and the required train passenger capacity. The seated to standing ratio will depend on the distance traveled and customer expectations. Equivalent ratios should be used when evaluating different vehicle technologies.

There is not a standard criteria to apply to every technology selection process, but in most cases there are primary factors that must be decided before subsequent decisions can be made. A decision tree analysis can be used to structure such decisions. Using a decision tree, capacity and speed requirements are first used to select viable vehicle technologies, with capacity growth considered. This selection may be further reduced after considering the associated guideway/track requirements for each vehicle. At both levels, estimated system costs should also be considered, as well as passenger safety issues. Finally, risk associated with using proprietary or single-supplier products needs to be assessed.

RISK MANAGEMENT AND NEW TECHNOLOGIES

Most advancements occur as incremental improvements to existing technologies, and existing technologies can be adapted to meet a broad variety of functional requirements. At the planning stage, new technologies need only be considered if they would enable a functional advantage that other technologies cannot. However, at the design and procurement stage, there may be opportunities to improve performance, reduce costs or add desirable features by specifying vehicles or systems that take advantage of new technologies.

Appendices B, C and D include a survey of alternative transit vehicles and systems, waterborne technologies and component technologies respectively. These appendices serve as a resource for assessing the range of alternative technologies that are currently being developed, considered or dreamed about (as of 2002). Those that have been deployed commercially are included in Chapter 1 of this report. Technology advancements to deployed technologies are included in Chapter 2, provided that they could provide new functionality, and that transit suppliers are investing development resources to bring them to market.

Risk associated with using a new or unique (one supplier) vehicle, component or system technology is difficult to quantify. Experienced judgment is needed, complemented by a technical evaluation. It can be painful to be the test case for a new technology if your customers and employees are inconvenienced while the bugs are being worked out. Contract performance penalty/rewards, reliability and warranty "guarantees/penalties" will provide some compensation in case things go wrong, but they do not carry passengers. Using test/prototype vehicles can minimize the risk of using new technology. However, the redesign cycle time must be very generous, which typical funding/contracting schedules do not permit. The use of equipment that has recently been produced also can reduce cost and risk.

Risk is not only associated with a generic vehicle type; there is also risk associated with specifying custom specifications that require a unique design, or that have a proprietary or single-source provider. If customizations are required in order to make a technology selection feasible, then the risk assessment should focus on the component technologies that are most critical. If a customization is not essential, or if there are several suppliers who have provided that customization previously, then the risk assessment for a particular component may be deferred until the vehicle or system procurement process.

The following measures assess how well a candidate technology minimizes the risk of cost escalation, delay, and deployment failure or poor performance in the final product. When comparing technologies against one another, the incremental benefits expected due to use of a proprietary or unproven technology should be weighed against the incremental risk incurred. When functional benefits and costs are equivalent, the lower risk investment is preferred.

- *Cost estimating risk.* Is there competition between firms to produce this technology as specified? Is there sufficient cost experience with this technology to be confident in estimates?
- *Implementation risk.* Is specialized technology design required for this application? Are there local firms with experience installing this technology?
- *Performance risk.* Is this technology proven in the field as specified? Is there a risk that it will not provide the desired performance? Is this technology proven to provide reliable performance?
- *Maintenance and service life*. Have maintenance and service life records been collected for this technology as specified that document reliability of the equipment?