MONORAIL TECHNOLOGY STUDY

Prepared by

The Texas Transportation Institute

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The Texas A&M University System
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"Monorail Technology Study"

Prepared

by

Quinn Brackett
Mrinmay Biswas
Rodger Koppa
and
Stephen H. Lucy

of the

Texas Transportation Institute
Texas A&M University
College Station, Texas 77843

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for

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DISCLAIMER

PREFACE

This report combines the findings of Task I: A Review of Monorail Systems,and Task II: An Operational Comparison. Task III was not completed in accordance with the findings and recommendations of the first two tasks.

Task I summarizes the "state-of-the-art" of monorail systems, their characteristics, capabilities, and functional usage in urban transit. This information was developed for the Texas State Department of Highways and Public Transportation to familiarize the department with this technology and its applicability to urban corridors in some of the larger Texas municipalities.

Early in this endeavor it was realized that the traditional literature searches and document review would not produce the necessary information. Very little information has been published in professional journals concerning monorails,and what has been published is either out of date or unsuitable. As a consequence, the majority of information collected came from organizations which are currently operating or building monorail systems. While this is without doubt the most current information, it is not in public domain and not without bias.

Perhaps because of the lack of a firm base in the transportation literature, there has been an accumulation of misinformation concerning the monorails and their uses. Myths have been perpetuated based on previous exposure to the technology in fair or amusement park settings or as the result of descriptions and appraisals of some of the earlier systems which have led transit and public decision makers to dismiss monorails without the consideration they may warrant.

It is the intent of Task I to serve as a primer to the current technology which, it is hoped, will dispel some of the myths.

Task II summarizes the results of a comparison of the operational characteristics of a Monorail Transit System to other line-haul transit modes suitable for use in urban areas.

The Appendices supporting this report are bound under separate cover.

Task I:

A Review of Monorail Systems

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INTRODUCTION

In 1960, Hermann Botzow published his masters thesis on monorails in book form. In the foreword to the book, A. S. Lang, Botzow's academic advisor, wrote; "It is surely no secret that the problems of transporting people and goods in and around our cities have assumed major proportions. The time has long since passed when we should have marshalled all our technological capabilities in search of workable solutions to them. Yet the field of transportation engineering suffers from a singular lack of unity and central purpose. There has been little attempt made, for instance, to assess soberly the characteristics of our available transportation media and to compare them on their basic merits. It seems that partly as a result of this neglect we are not solving our problems as quickly as we should.

"Among the forms of transportation thought appropriate to the urban environment, monorail is both the most loudly hailed and the least well understood. It has been promoted to the point that it has its wild enthusiasts; yet no one has seen a monorail transit system in actual operation. The fact is that we have little reliable information on the subject, because no one has yet taken a look, which attempted to be at once objective and relatively complete." (1)

A good portion of this statement is still true some twenty years after it was written. While there have been attempts at solving urban transportation problems using new and innovative approaches they have generally focused on making more efficient use of the existing highway system. These approaches include the dedication of special use lanes for high occupancy vehicles (HOV) or reverse traffic flow. There have also been attempts to compare transit modes on their merits. However, in the United States the application of monorail technology to transit systems appears to have been frozen in time. The technology itself has been advanced and applied in the urban mass transit mode in other countries, but transit authorities in the U.S. still respond as if it is an unproven system with little reliable information available.

Perhaps this is due to the difficulty in obtaining information or the casual observation that monorail systems have been limited to the circulation of tourists and have no place in a transit system.

The information exists, but it is difficult to acquire because it is generally anecdotal and must be obtained first hand. The characteristics of the foreign transit systems that have been built using monorails are not directly applicable because of geographical, cultural and, in some cases, physical differences of the ridership population. However, the structures, performance characteristics and operations can serve as models of the technology.

The most valuable contribution this report can make is to bring to the attention of the reader the changes that have taken place in monorail technology and to correct some of the erroneous notions that have grown up for the last twenty years.

MONORAIL DESCRIPTION

As can be surmised from the word itself,"monorail" means "single rail". It is one of those generic terms that covers a variety of systems and is apt to lead to miscommunication. It will conjure different mental images depending on the experience of the individual using it and the context of the conversation.

Perhaps the most prevalent monorail system in use today is the overhead crane type that can be found in large industrial complexes over the globe. These, of course, are not the subject of interest because they are not generally used to transport passengers. Historically, however, the passenger variety of monorail systems had their humble beginnings as cargo carriers.

The interest here is in the passenger carrying monorails. Again there are various types of these systems. They can be categorized according to structure and the method of propulsion.

A good description of the subject systems is required (if the pun can be forgiven) to get everyone started on the right track. This includes a sound working definition, a classification of the types of systems, and a brief history.

DEFINITION

Monorail is a term applied to various types of passenger and cargo vehicles that travel on a single track or beam. Since the current discussion is concerned with transportation of passengers in urban areas, this definition can be amended for that context.

Urban monorails are those vehicles that travel on a single rail or beam that can be used to carry passengers in urban areas.

It should be noted that this definition includes some systems that are not currently being used for urban transit.

TYPES

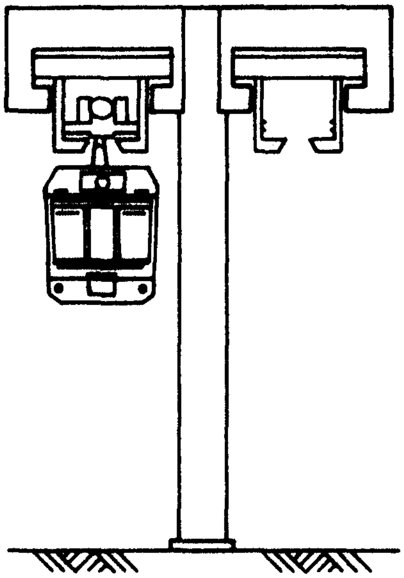
Monorail systems that currently satisfy the definition can be classified according to their structure and their method of propulsion.

Most monorail systems have elevated rail support structures which allow the vehicles to either be suspended from the rail or supported by it. As the name implies, the suspended system mounts the vehicle directly below the rail member. The metal rail is usually a rectangularly shaped, split bottom, box beam girder. The vehicle is attached by suspending the vehicle directly below bogie or truck assemblies which are contained in the rail beam. The drive wheels or traction tires run along the lower flanges of the girder. The system shown in Figure I-A represents the symmetrical type of suspended system.

An asymmetrical design has been used where the load of the vehicles is transmitted to the traction wheels by means of a lateral arm attached to the top of the vehicle. This arm then curves around the rail support and attaches to the bogie containing the drive wheels. This is the design of one of the oldest monorail systems; however, it has not been used in recent years. (1,2)

In the supported system the vehicle straddles a concrete or steel running rail. The rail is wide enough to permit the drive wheels to run on top and

A. Suspended



B. Supported

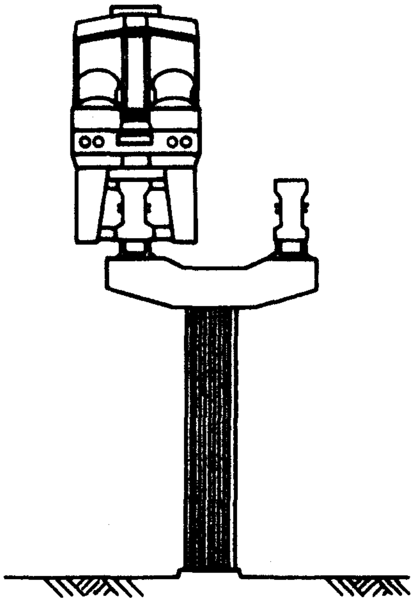


Figure 1. Monorail Structures

Source: Japanese Monorail Association Brochure deep enough to allow support wheels to be mounted on either side to maintain lateral stability (see Figure I-B). This arrangement creates the impression that the vehicle is almost wrapped around the rail.

Most supported systems are variations of the Alweg design. This design was developed by a Swiss industrialist named Alex Wenner-Gren in collaboration with the Krupp Corporation of West Germany. (1,2,3)

The propulsion systems that have been used for monorail systems include: gasoline engines, electric motors, cable drive and magnetic levitation. Of these, by far the most prevalent has been the use of electric motors. A few demonstration systems using gasoline engines were built in the 1950's and 60's but they were discontinued. Cable drive systems are being used to propel vehicles where the distance travelled is short,and trips can be from point to point with few stops in between. Magnetic levitation is a relatively new technology in which magnetic forces are used to both lift the vehicle and propel it. Current designs use a single rail for these systems; however, they are proposed for use in an interurban network because of the high speed they are able to achieve. Maglev systems have attained speeds in excess of 250 mph. (4)

The system most likely to be found in use as urban transport would use electric motors for propulsion and be of the suspended or supported type. These systems represent existing, state-of-the-art technology requiring no research and development for implementation. The other systems mentioned either have restricted uses or are pushing the state-of-the-art in terms of technological development. Consequently, the focus of this report will be on the electric systems of either the suspended or supported variety.

HISTORY

Monorails have been in use since 1821 when an Englishman built a horse drawn system for transporting materials in a London navy yard. This monorail and another one like it were built by Henry Palmer using board rails supported at intervals by poles.

The first passenger monorail was built in 1876 for the Philadelphia Centennial Exposition. In 1890, a commercial line was developed connecting Brooklyn and Coney Island. During this same period several other cargo and passenger monorail lines were established in California and Ireland.

In 1901, a suspended type passenger system was constructed in Wuppertal, Germany. This system is still in operation carrying over 16 million passengers annually.

Ostensibly, the cargo monorails were developed either to conserve space and reduce transportation costs. The passenger monorails were built for their cost savings but also for their novelty and to provide a scenic vantage platform. Undoubtably, part of the motivation for building these systems rested in the engineering challenge they presented and the sheer love of the concept. This motivation was necessary to sustain the monorail enthusiasts during the automobile and highway expansion period following World War II.

In the late 1950's there was a resurgence of interest in "new" technology which was created by the prosperous economic conditions and the "Sputnick" challenge in space. This led to repeated demonstrations of Space-age monorail systems in Houston and Dallas, Texas, Disneyland in California, and in

Cologne, Germany. With the exception of the Disneyland system, these prototypes were removed or were abandoned after a short period. The Disneyland system has been continuously upgraded and improved. It is still in operation.

The demonstration of monorail technology continued in the 1960's with installations at the Seattle World's Fair, the Tokyo Zoo, Hemisfair in San Antonio, Texas,and many other areas. For the most part these systems were intended to circulate tourists about fair grounds and amusement centers. Once the attractions were over, the lines were usually discontinued. (1,3)

In the 1970's,monorail systems began to be considered again as a means of transporting passengers in a transit rather than a tourist mode. This has occurred primarily in Japan.

In the United States monorails have been considered in general as part of the Federally required alternative evaluation process conducted prior to implementing a new transit system. However, these comparisons have generally dismissed monorails as unproven technologies. Consequently they have not been considered eligible for federal funding support, and not included in the detailed evaluation.

SYSTEM CHARACTERISTICS

Monorails, like most other transit systems, have three major components: vehicles, track and stations. Vehicles, generally referred to as rolling stock, include propulsion and propulsion with passenger units. The track in this case is the elevated structure used to carry the rolling stock. The stations, of course are the platforms used for loading or unloading passengers.

ROLLING STOCK

The major difference between monorail vehicles and traditional railroad vehicles is that the propulsion units on monorails are included in each car. There is no locomotive per se. The lead vehicle in a train has a space for the operator; otherwise,it is identical to the rest of the cars.

The size, weight and passenger carrying capacity vary with the type of system being used as does the vehicle performance. The range of passenger capacity is from 40 per car for the scaled down Alweg version used at Disneyworld where standing passengers are not allowed,to 229 in the Japanese Hatachi-Alweg. The 229 passenger capacity is based on a crush condition allowing only one square foot for each passenger.

The propulsion units are usually 600 volt, direct current motors which are capable of propelling the vehicles in excess of 60 mph. The normal operating speed is in the 45 mph range.

A summary of the characteristics of the rolling stock is presented in Table 1 for four systems now in operation. It should be remembered that only the systems in Germany and Japan are being used in a transit mode.

Table 1. Rolling Stock Characteristics

System	Wuppertal, Germany	Tokyo, Japan	Seattle, Washington	Disneyland, Florida
Type	Suspended (MAN)	Supported (Hatachi-Alweg)	Supported (Alweg)	Supported (Modified Alweg)
Vehicle Description				
Empty Weight (lbs.)	48,896	55,000	25,000	18,400
Gross Weight (lbs.)	79,380	87,780	40,000	24,520
Normal Passenger Space:				
Seated	48	56	61	40
Standing	98	143	82	No Standing
Area (ft.^{2})	2.26	1.21	UKN	UKN
Crush Passenger Space:				
Seated	48	56	61	40
Standing	156	173	UKN	No Standing
Area (ft.^{2})	1.35	1.0	UKN	UKN
Vehicle/Train	2	4-8	4	5-6
Vehicle Performance				
Max Capacity(psgr/hr)	3,672	62,000	10,000	10,000
Min Headway(sec)	UKN	90	Single Trains	90
Cruise Velocity(mph)	16-17	45	45	40
Max Velocity(mph)	37.3	50-70	60+	60+
Max Grade (%)	+3	10	UKN	6
Propulsion				
Motor per car	2	4	2	1-2
Motor Placement	1/Bogie	all axles	1/Bogie	Bogie
Power Type	600 VDC	750-1500VDC	600 VDC	600 VDC
Switching				
Type	UKN	Flexible Beam	No Switching	Beam Replacement
Time (sec)	UKN	8-10	No Switching	30

STRUCTURAL COMPONENTS

As with all structures, the monorail structural system is composed of several components: the guideway, the pier supports, and the foundation.

The guideway is the most essential and unique aspect of the monorail system. The ideal guideway would be of uniform dimensions, which should be toward practical minimums, provide for complete housing of and access to all basic system support hardware, be visually attractive and acceptable, and be structurally sound and economically realistic. This is, obviously, a tall order for any structural component. Trade-offs and concessions must be made, but no compromise may be made on structural capacity and provision for support hardware. This leaves aesthetics, economics, and possibly some peripheral functions as negotiable features.

There have been several guideway structural configurations developed for each type of monorail system. In the case of the supported monorail, the most common configuration is a hollow reinforced or prestressed concrete I-beam. (Figure 2A) This allows the drive wheels to run along the top surface of the beam and the stability wheels to run along the side of the beam. In the Alweg system, for a 100 ft. span, a beam 3 ft. wide and 5 ft. deep is required. In the majority of construction cases, precast prestressed beams are used for straight and large radius curved sections while reinforced concrete is used on the remaining curved sections.

Suspended monorails usually use steel guideways when supported asymmetrically and concrete or steel with steel or wood running surfaces, guideways when supported symmetrically. Modern assymetric supported monorails have

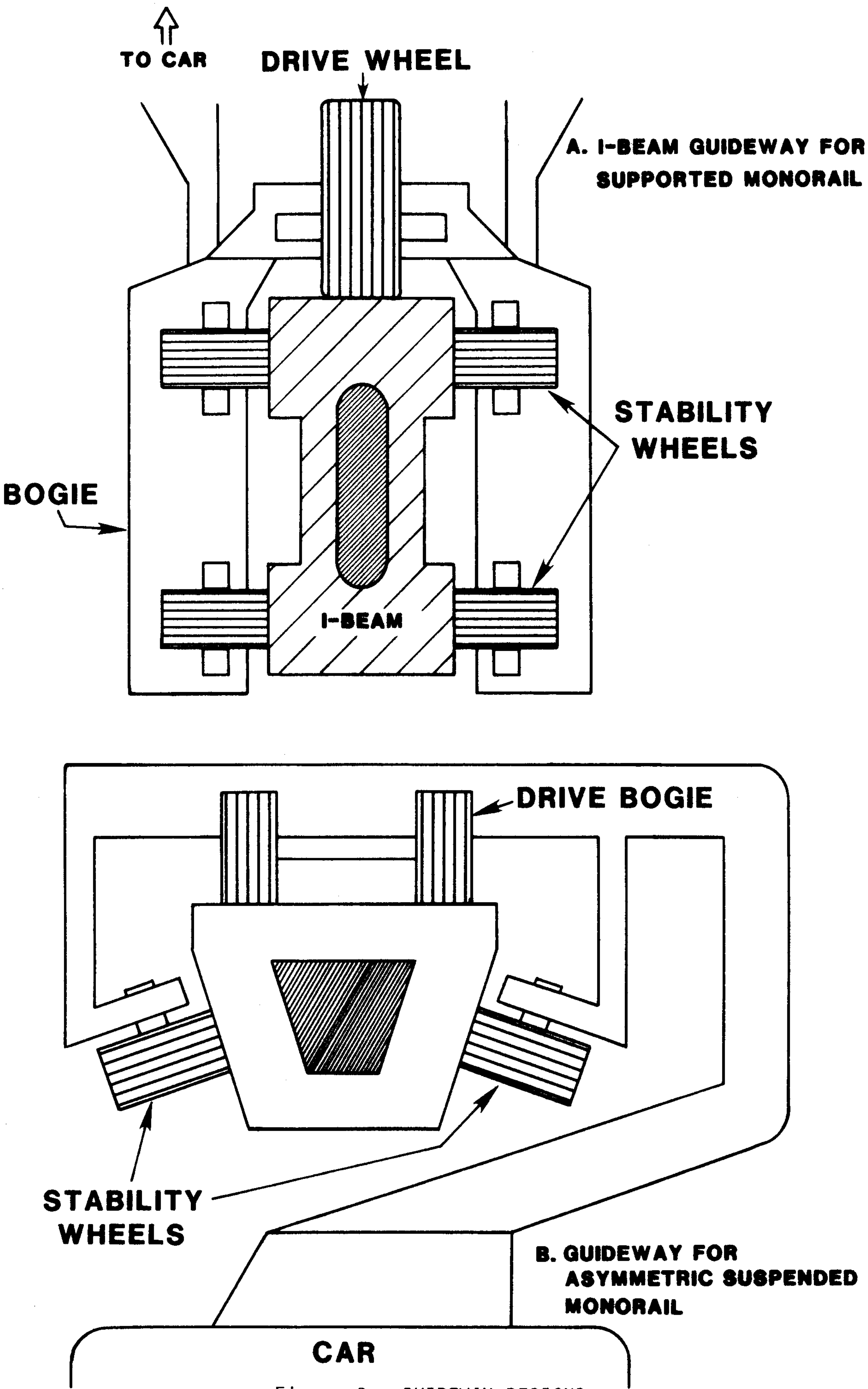
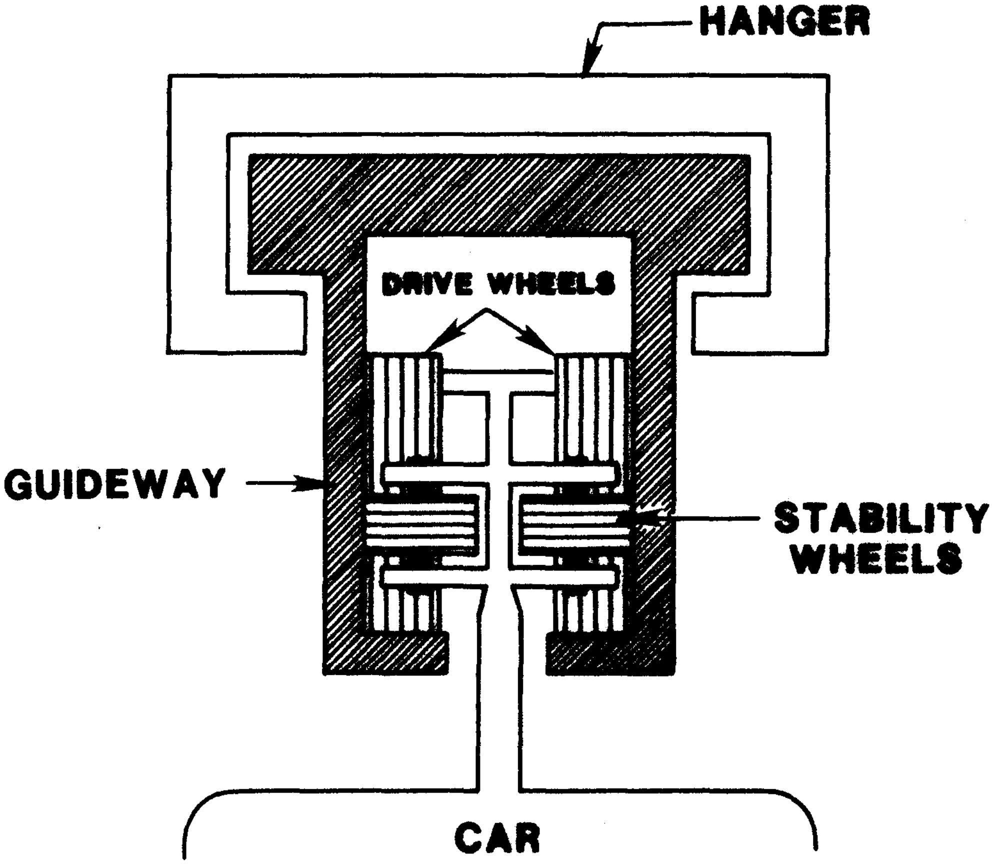


Figure 2. GUIDEWAY DESIGNS



C. SUSPENDED SYMMETRIC MONORAIL

Figure 2 (Cont'd). GUIDEWAY DESIGNS

a triangular shaped steel rail which allows the drive wheels to run along the flat top surface of the rail and the stability wheels to run along either side of the sloping side surfaces as shown in Figure 2B. The symmetric supported monorails have a split-bottom box girder made of prestressed concrete or steel plate with a wooden or steel plate running surface on the inside of the lower flanges. The box girder must be large enough to allow the bogie or truck to ride inside the girder. See cross section of this design in Figure 2C.

There are really only three basic types of pier supports: T-shaped support, inverted J-shaped support, and single column support. These are shown in Figure 3A, B, and C. If two-way traffic is desired, the T-shaped pier support will economically support one rail at each end of the cross member. The inverted J-shaped pier support is used when only one-way suspended monorail traffic is desired. The single column support is used for one-way supported monorail traffic.

One pier support system which is currently under investigation is the use of a cable-stayed guideway, a concept similar to a suspension bridge. This approach, which would require extremely tall supports, would only be feasible in open or suburban areas. This approach is also applicable to all three types of monorail systems and would allow space of up to 300 ft. for the guideway.

Placement of the supports is perhaps the single most important element in the structural evaluation of guideways types. The constraints and limitations on support placement in an urban environment are restrictive. First and most obvious, pier supports must be kept clear of intersecting streets, not only for vehicle clearance but for sight distance as well. This also applies to any driveways or building loading zones. Very often, utilities will dictate areas to be avoided, particularly justified. Another significant constraint

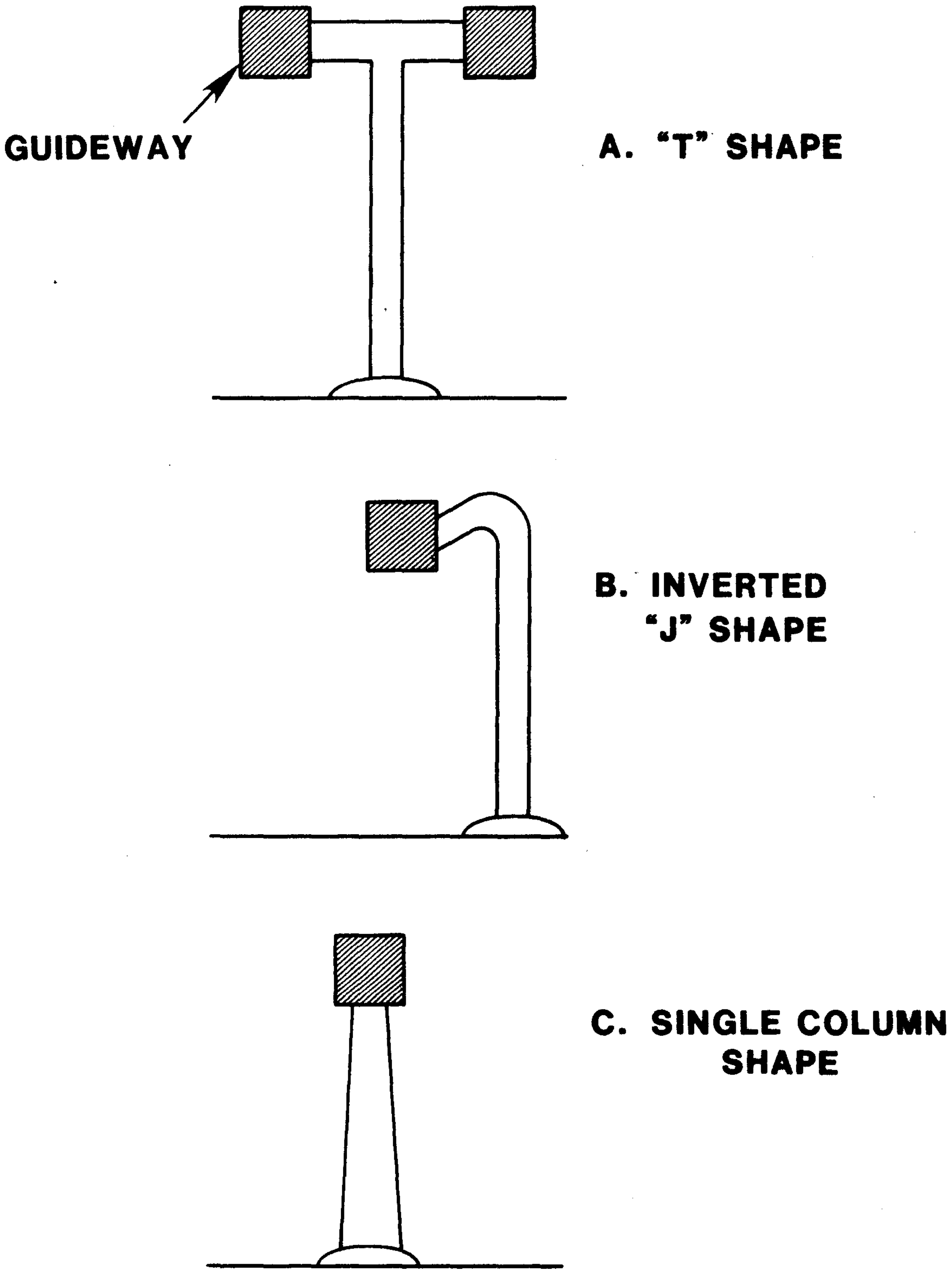


Figure 3. PIER SUPPORT DESIGNS

is support placement related to adjacent architecture. Both urban designers and building owners are sensitive to aesthetic integration of the structure with building features. These constraints, taken collectively, will usually dictate support placements that give wide variations in guideways' span lengths. These constraints will also have an influence on the type of pier support best suited for the job and, furthermore, on the size and type of the guideway to be employed.

Any currently accepted form of foundation system can be made sufficient to meet the loading and peripheral requirements imposed by the system. In most cases, the most critical loading on the foundations will be movement caused by the lateral wind load on the vehicle with respect to the pier support and the centrifugal force from the vehicle.

STATIONS

The elevated nature of most monorail systems dictates that loading platforms or stations also be elevated. When the system descends, as is the case in the Disneyworld hotel, the stations can also be lowered. The station layout depends on the number of lines and desired loading points. There can be, for example, center loading stations between two tracks. There could also be three platforms, two outside and one center. Single line platforms can be located on either or both sides.

Station appointments could also vary with specified usage. As a minimum, they should include shelter from the elements for passengers, protection for fare collection mechanisms as well as queueing and safe boarding devices.

The major consideration concerning stations is the length of the boarding platform. It is the platform length that governs train length and thereby line carrying capacity.

MONORAILS IN SERVICE

A compilation of operational monorail systems, not associated with fairs nor intended for short term use, is presented in Table 2. This list was derived from various sources. It is reasonably comprehensive but not exhaustive. It provides an idea of the numbers, types and usage of the technology. This Table also includes the Japanese monorails that are under construction as well as a list of those being planned. (1,2,3,5,6)

Although Table 2 summarizes the salient points for each system, additional information concerning these systems is presented in the following sections.

UNITED STATES

There are presently four major monorail systems in use in the United States: two located at Disney amusement centers, one recently constructed at Memphis, Tennessee, and one operational at Seattle, Washington.

The monorail located in Disneyland in California is a down-scaled version of the Alweg supported design. It has two stations and is used to provide a scenic tour of the park. The monorail system at the Disneyworld Park in Florida is longer but of similar design. It serves as the main link between the parking areas, hotel and park. Recently expanded, this system will provide transportation to a new attraction called the Epcot Center. Disneyworld's monorails presently carry over 25 million passengers a year and have a reliability record of 99.9% sustained over a ten year period. (5)

Table 2 Monorails Usage

OPERATIONAL SYSTEMS

Date Built	Location	Length (Miles)	Type	Use
1901	Wuppertal, West Germany	9.3	Suspended, Electric	Transit (18 stations)
1959/61	Disneyland, California	2.5	Supported, Electric	Tourist
1962	Seattle, Washington	1.1	Supported, Electric	Transit/ Tourist
1962	Inuyama, Japan	.86	Suspended, Electric	Unknown
1964	Tokyo, Japan	8.2	Suspended, Electric	Transit, (Airport)
1964	Yomuriland, Japan	1.9	Supported, Electric	Tourist
1971/82	Disneyworld, Florida	7.0	Supported, Electric	Transit/ Tourist
1980	Rhyl, North Wales	1.1	Supported, Electric	Tourist
1981	Memphis, Tennessee	.68	Suspended, Cable	Tourist
	UNDER CONSTRUCTION			
1983	Kitakyushu, Japan	5.2	Supported, Electric	Transit (12 stations)
1984	Osaka, Japan	8.3	Supported, Electric	Transit (9 stations)
1986	Chiba City, Japan	19.4	Supported, Electric	Transit (18 stations)
1987	Naha City, Okinawa	4.1	Supported, Electric	Transit (14 stations)
	PLANNED			
	Kawasaki, Japan	23.8		Transit
	Okayama, Japan	13.1		Transit
	Kumamoto, Japan	6.3		Transit
	Gifu, Japan	8.8		Transit

The cable powered, suspended system built in Memphis is used to shuttle tourists from the city proper to a recreational area at Mud Island. This unique system is suspended from the underside of a highway bridge crossing the Mississippi River. It has the capacity of carrying 3000 passengers each hour, making it the "highest capacity ropeway transportation system in the United States." (7)

The Seattle monorail was originally constructed for the World's Fair in 1962. It is a two station system designed to transport passengers from downtown parking to the fair grounds. Reportedly, the original capital costs of the system were recovered in the first five months of operation. Rather than remove the system it was donated to the Seattle Center which now operates the fair area as a cultural and amusement center. Currently, over 2 million passengers make the 1.2 mile trip each year. The 35 cent fare generates enough revenue to offset the operational cost. One cost savings aspect of the operation is the method of accelerating to 60 mph in the first quarter mile, then coasting the rest of the trip. This reduces the electricity usage while keeping the trip time down to around 90 seconds. (6,8)

EUROPE

Certainly, the Schwebebahn (swinging railroad) of Wuppertal, Germany illustrates the serviceability of monorail systems. This system, which has been operating continuously since 1901, carries over 16 million commuters annually. Botzow reported in 1960 that over one billion passengers had traveled the line at that time with a report of only two injured passengers.

One of the injuries resulted from the panic of a baby elephant which was being transported as a promotional stunt in 1952. He also points out that this low speed system (17 mph) was operating at a profit. (1,3)

Although there have been other demonstration systems built in Germany, France, and Italy, they have been discontinued. However, recently a steel rail system has been completed in Rhyl, North Wales. This is the first public monorail to be built in the United Kingdom. It is a small, supported system designed to link the many attractions of the Rhyl resort area. It has a capacity of 1400 passengers per hour and relies on technologically simple and proven equipment. (9)

ASIA

Without doubt the greatest usage of monorail technology has taken place in Japan. Beginning in the early 1960's, the Japanese constructed several transit monorail systems. A suspended version was built in Inuyama to carry passengers from the main rail station to the seaside resort of Enoshina. A major line was created from Tokyo to the International Airport at Haneda. This system had to be administratively reorganized when a new freeway route to the airport reduced its passenger demand. The reorganization and the rapid saturation of the freeway changed the situation so that the monorail line now enjoys a 14.4% share of the airport ridership. (2,10)

During the 1970 Exposition, in Osaka, an Alweg type monorail system carried 33.5 million passengers in six months. Although this was a tourist type system, its capabilities helped set the stage for subsequent monorail development.

The cause for the interest in monorail systems in Japan was created by a combination of dramatic increases in automobile traffic and the high costs associated with the construction of subway rail systems. In 1972, the Japanese parliament enacted legislation to promote urban monorail systems. This legislation included a mechanism allowing monorail track to be considered a special type of road and therefore eligible for interest free loans from public construction funds. Since the 1972 legislation, construction has begun on four systems, and many others are in various stages of planning.

SYSTEM EVALUATION

All systems can be evaluated in both general and specific terms. General evaluations consider the advantages and disadvantages of a particular system without comparisons to other systems. Specific evaluations, on the other hand, attempt to be more quantitative by using other systems as a frame of reference. They are concerned with such things as the efficiency of a given system or its ability to produce desired results at the smallest cost.

To go further, specific evaluations may be equivalent or generic in nature. An equivalent evaluation attempts to compare the efficiency of systems with respect to some predefined requirements, or to compare systems designed for a specified operating environment. The generic evaluation attempts to compare salient aspects of representative examples of each systems with the realization that they are not equivalent. This type of evaluation,grounded on real-world examples, trades experience for rigor to provide a general idea of the rank order of efficiency of widely different systems. The generic type of evaluation was considered appropriate for this section.

GENERAL EVALUATION

The commonly stated advantages of monorail systems are that they:

1. Can be constructed quickly and simply
2. Have low construction costs
3. Are grade separated
4. Require minimal area at grade level
5. Have high ride comfort, little car sway

6. Are highly reliable
7. Are very safe
8. Cause little shading or visual obstruction
9. Produce little noise

The commonly stated disadvantages of monorail systems are that they:

1. Are a new and unproven technology
2. Have problems with switching
3. Provide no means of emergency egress
4. Are visually obtrusive and not aesthetically pleasing

The use of prefabricated concrete beams of great lengths (100-150 ft) allows monorail systems to be constructed quickly, with little disruption of traffic or commerce. The short construction period coupled with the simplicity of design produces a low cost of construction. If an elevated structure is required in any case, the monorail system, since it is much smaller than heavy rail elevated structures, affords the least obstruction of light and view for those who must live or work near the system. Elevated systems of any kind have long been known to be safe and reliable.

The electric propulsion and pneumatic tire design produces little noise and no pollution.The monorail vehicle is not subject to the rocking or swaying created in two tracked systems.

Since there are monorail systems currently being used elsewhere in the world, the technology can hardly be considered unproven. The existence of operational systems being used in the U.S. in modes other than transit suggest that the technology is readily available and prototype systems would not have to be built.

Switching of monorail vehicles from one track to another is not the problem it has been. Flexible beams or beam replacement systems now allow switches to be made in less than 30 seconds, which is sufficient to accommodate trains operating on 90 second headways.

Although slide chutes can be installed to permit egress from monorail vehicles in emergency situations, their safety and reliability records would not seem to warrant it. Slide chute operation without the presence of an attendant might pose a hazard; however, the one operator on board might be able to oversee their deployment.

When aesthetics are considered, there is no doubt that an elevated structure placed in a collection of expensive office buildings or in residential neighborhoods would not be readily appreciated for its beauty. Experience in Seattle, Washington, and around San Francisco Bay has shown, however, that elevated systems come to be accepted in time whether monorail or heavy rail. Eventually, new structures are designed around the monorail system to provide a more pleasing and integrated archetecture.

SPECIFIC EVALUATION

The efficiency of a transit system is determined by some measure of its carrying capacity and the cost associated with generating that capacity. As far as capacity is concerned, the current systems in use demonstrated a capability of providing a wide range of capacities. Using variations in train lengths and spacing, a given monorail line can satisfy most demands placed on it. It should be pointed out that while some heavy rail systems are capable of servicing larger demands, they seldom operate at or near capacity. (Refer to Table 3). (11)

TABLE 3 Utilization of Major Urban Rail Systems

	World Wide Average	New York	Paris Metro	Moscow	Tokyo TRTA
Average Passenger Per Car	40.9	38.3	28.8	54.5	72.3
Car Capacity	185	350	164	170	144
Average Occupancy as % of Capacity	27.4	11.0	17.6	32.0	50.2

Source: (11)

The two major cost components of transit systems are the capital costs and operational costs (sometimes refered to as operation and maintenance or O&M costs). Obviously, capital costs depend on the length of the system, number of lines, pieces of rolling stock, right of way, stations, construction time, etc. But for a given system they are fixed. Operational costs, on the other hand, are variable. They vary with the level of service provided and to some extent the reliability and safety of the system.

Capital costs for monorail systems are lower than those for heavy rail systems constructed either above or below grade level. The construction cost of elevated structures for monorails is cheaper due to the lighter weight of the rolling stock and the relatively longer span distances involved. The cost of elevated monorail structures has been estimated to be 1/3 to 1/4 the subway construction cost for the same transportation capacity which is one reason why Japan, which has limited space, is pursuing monorail development. (2) However, the capital cost of a heavy rail system built at grade is less than that of an elevated monorail as would be the cost of most light rail systems which are built at grade.

Operating costs of monorail vehicles are about equivalent to those of light rail vehicles which in turn are lower than those of heavy rail. However, since the heavy rail vehicles carry a greater number of passengers, the cost per passenger is about the same.

A summary to these comparisons is presented in Table 4. Included with the data for the monorail systems is similar information for two examples of heavy rail and two examples of light rail systems. It should be recalled that this is not intended as an equivalent comparison, but is included to

Table 4 Generic Transportation Comparisons

	Monorail			Heavy Rail		Light Rail	
	Tokyo	Seattle	Disneyworld	Atlanta	Washington	San Diego	Cleveland
COST							
Capital Cost (Million $)	33.6-61.5* +	8.5-11.6 +	UKN	1,499.4	2,698.8	94.4	109.2
Annual Operating Cost (Million $)	UKN	.6	3.4	49.1	116.1	3.7	8.0
CAPACITY							
Length (Miles)	8.2	1.1	14.2	14	39	16	13
Peak Hour Line Capability	45,000	10,000	10,000	48,000	63,000	4,000	12,000
Annual Passengers (Million)	UKN	2.1	5.5**	40.2	98.5	12.0	4.7
Annual Psgr. Mile (Million)	UKN	2.3	40.7	442.2	1,083.5	93.6**	44.7**
EFFICIENCY							
Capital Cost per Mile (Million $)	4.1-7.5	7.7-10.5	UKN	107.1	69.2	5.9	8.4
Capital Cost per Mile per Unit of Peak Hr. Capacity ($)	167	1050	UKN	2231	1098	1475	700
Operating Cost per Passenger Mile ($)	UKN	.26	.09	.11	.11	.04	.18
Operating Cost per Route Mile (Million $)	UKN	.5	.24	3.5	3.0	.2	.6
Implementation Time (Yrs.)	2-3	2-3	3-5	9+	12+	2.5	2.2

+Range due to different cost estimates from different sources

*Projected 1981 dollars using consumer's price index

Estimate

Source: (3, 5, 6, 8, 12)

provide an idea or estimate of how the efficiency of a monorail compares to other transit modes.

SUMMARY AND CONCLUSIONS

Perhaps the most succinct summary that can be made concerning monorails is that they are not substantially different from other rail transit modes. Monorail systems are not new nor is their usage in urban transit unique. The existence of transit lines in Japan attest to this fact just as the 81 year history of the Wuppertal line demonstrates the technology.

These foreign urban transit monorails have similar capabilities to most heavy rail systems. They have equivalent speeds and carrying capacities. Their U.S. counterparts, which are not used in urban transit, have scaled down carrying capacities which are quite similar to light rail systems.

The only characteristic of monorails that appears to be unique is the cost savings afforded under certain conditions. The structural costs of monorails are apparently lower than those of either subways or elevated, heavy rail systems. However, those savings are lost when comparisons are made with heavy or light rail systems built at grade. The operational costs are close to those of light rail systems which is probably due to their lighter vehicle construction. A more comprehensive study of these costs will be the product of the second task of this project.

The streamlined appearance of monorail and their novelty may serve to attract a higher ridership than some of the more traditional systems. But, the elevated structure would undoubtedly bring complaints of visual obstruction and property devaluation. However, considering the elevated heavy rail alternative, monorails are smaller and less obtrusive.

These somewhat positive statements lead to the standard question; "if monorails are so functional, why aren't they being used for urban transit in this country?" There is no definitive answer to this question. Some plausible explanations may include:

1. Monorails have always been built and demonstrated in parks and fairgrounds and consequently have come to be associated with tourist type operations rather than transit.
2. Monorails are not a proven technology in U.S. urban transit. Frequently, they are dismissed without serious consideration simply because there are none around. Obviously, they cannot be proven in this country until one is built: the "Catch-22" of monorails.
3. There are a number of foreign and domestic companies that manufacture and market heavy rail systems but few that produce monorails; therefore the marketing odds are against them.

It is understandable that transit authorities responsible for deciding where and how to invest enormous sums of money would be concerned with making the wrong choice. A decision to allocate funds to a system other than those traditionally selected could lead to a great deal of criticism. It would be ideal if these decisions could be made solely on the basis of sound performance and cost requirements. Unfortunately, the emotional and political climates do not always afford that opportunity.

One point is clear; transit officials need reliable information from which to work. A great deal of the information concerning monorails is outdated, and current information is hard to obtain. The information that was obtained for this report indicates that monorails are not the universal panacea for urban transit problems that some of the enthusiasts seem to propound nor are they the useless folly their critics claim. Somewhere on the middle ground lies the objective appraisal.

SYNOPSIS

- Current monorail technology affords a safe, reliable means of providing an intermediate to large capacity as a single line or as part of a system.

- Monorail systems can be installed quickly along existing right-of-way with little disruption to traffic or commerce.

- Since these systems are elevated, their capital costs are higher than some light and heavy rail alternatives built using existing or at-grade beds, but are cheaper than elevated or sub-grade rail systems.

- While modern monorail technology provides a viable and competitive alternative in urban mass transit, it is by no means the optimal solution for every corridor.

- Each corridor must be considered in its own context, alternatives weighed, and decisions made based on future demands and resources rather than emotions and politics.

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Task II:

An Operational Comparison

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I. INTRODUCTION

In the first task report on this study of monorail technology, it was pointed out that the capital investment required to build a section of any type of mass transit system varies by geographic location and by type of system. Geographic location affects such factors as land prices, the nature of construction (underground, at-grade, elevated), strength of materials required, and labor costs. Type of transit system directly involves the nature of construction, but also dictates the cost of rolling stock, stations, track and supporting structures, etc. For this reason, comparisons of capital cost experience of different transit modes can only be used in a general sense in an alternatives analysis for a new system. The development of capital cost estimates for monorails and several other transit modes was generated in the first task report and is summarized in Table 1.(1) Estimates of the implementation costs of various alternatives can only be reliably determined if detailed bids for the specific site of interest are generated by venders of various transit modes. Even if this information is available, additional information is required concerning the operational capabilities and costs of transit alternatives. Only then can capabilities be compared with needs and costs with budgets in order to select the most practical alternative. In the absence of detailed implementation cost bids, much can be done with operational data on transit modes, if some rational basis of comparison can be found.

This report provides such operational data for monorails.

TABLE 1 COMPARISONS OF CAPITAL COSTS

	MONORAILS		RAPID RAIL		LIGHT RAIL	
	Tokyo	Seattle	Atlanta	Washington,D.C.	San Diego	Cleveland
Total System Cost (Million$)	113.4*	8.5-11.6	1,499.4	2,698.8	94.4	109.2
Length (Mi)	8.2	1.1	14	39	16	13
Capital Cost Per Mile ($/Mi)	13.8	7.7-10.5	107.1	69.2	5.9	8.4
Implementation Time (Yrs.)	2-3	2-3	9+	12+	2.5	2.2

*All figures projected to 1981 dollars using the Consumer Price Index

Source (1)

Comparisons of the operational characteristics and costs of monorails to those of other transit modes have taken several forms. Far and away the most common of these forms has been qualitative in nature, relying primarily on subjective appraisals on the disadvantages of monorails and, by implication, the advantages of other systems. A example of this type of comparison can be found in a recent "state of the art" analysis which concluded: "Aside from a relatively smooth and quite ride, albeit at low speeds, monorails have comparatively few advantages over other proven primary transit modes. The primary disadvantages of monorails include a history of oscillation or sway of suspended monorails in high winds and at high speeds, which may cause riding quality, station clearance, and vehicle switching problems. The stability of suspended vehicles can be improved by dual rail construction, but such construction further complicates the switching mechanicsms. Switches or turnouts for both the suspended and bottom-supported monorails are elaborate, cumbersome, and slow acting because of the large guideway assemblies that must be moved to change routes. In addition, monorails are not readily adaptable to at-grade or underground aligments as are other primary transit modes because of their comparatively large vertical dimensions. And finally, monorails cannot provide the high-speed operation required for line-haul sections of primary transit routes. Most monorails that are now in operation or what have been demonstrated can attain speeds of only 20 to 30 mph. Therefore, their best application is as elevated alignments, which may produce aesthetic problems in urbanized areas- especially top-supported systems, which require an elaborate superstructure." (2)

Unfortunately, these subjective comparisons tend to perseverate through the transit community making more objective information difficult to obtain and certainly less credible even when definitive data is available.

Those few objective operational comparisons that have been attempted have usually focused on passenger carrying capacity, speed, and operating cost per vehicle mile. These characteristics, derived for various systems in current operation, are used to make relative comparisons among the modes of interest. This technique has two distinct limitations. First, site and population differences for the various systems can cause wide differences in cost, ridership and other variables. However, since it is unlikely that two transit systems will ever operate under identical conditions, it must be assumed that these differences can be adjusted for by presenting a range of system operating characteristics or by using averages.

The second limiation applies strictly to monorail systems and it deals with the lack of usable data. Aside from the short line in Seattle, there are no monorails in this country functioning in the transit mode. Consequently, estimates and extrapolations have to be made. A good example of an approach to overcoming this limitation was demonstrated in a report prepared for the Interim Regional Transportation Authority of Dallas, Texas. (3) The authors of this report requested that the engineering company associated with building monorails for major amusement parks estimates the characteristics and cost associated with a hypothetical line designed to meet given requirements. A synopsis of the data developed for monorails and other systems considered in this report is presented in Table 2.

TABLE 2 MODAL SERVICE CHARACTERISTICS

	RAPID RAIL	MONORAIL	LIGHT RAIL	BUSWAY
Max Vehicle Speed (MPH)	55-75	45-55	40-60	55-65
Accel/Decel(Ft./rec^2)	4.0-4.4/4.0-4.4	3.0/5.0	3.3-5.0/3.3-5.0	0.7-3.7/2.9-4.4
Praticle Headway (Min)	2.0	2.0	1-2	7.4 (sec)
Maximum Peak-Hour Lane Capacity (Pass./hr., peak direction)	42,000	10-20,000	19,000	27,000
Dwell Times (Sec.)	10-60	10-90	10-30	10-160
Operating Costs per vehicle mile	$2.50-$5.00	$1.00-$2.70	$2.50-$5.00	$2.50-$4.00

Source (3)

Using data from this table and other sources, the authors tentatively concluded: "Monorails provide similar service characteristics to grade separated heavy rail and light rail transit systems. Most such systems operate at lower speeds than grade-separated rails however. The monorail operating at Disney World in Orlando, Florida, can attain a top speed of 45 mph, thereby offering an average speed capability in the same range as heavy and light rail." (3)

A second method of overcoming the lack of available U.S. data for monorail systems operating in the transit mode is to use information from foreign countries. The Schwebebahn of Wuppertal, Germany, built in 1901, is too old a system to provide a useful comparison even though it is still used daily for transit purposes. The Japanese Haneda Airport Line in Tokyo, can serve for comparison purposes since it is representative of modern monorail technology being employed in a transit mode.

Data obtained from the Japanese Monorail Association reflecting the operational characteristics of the Tokyo monorail will thus be used in this report to compare with average performance figures developed for rapid rail, light rail and busway transit modes. The method of comparison, rather than just presenting individual data points, will involve the creation of transit service envelopes.

Transit service envelopes provide a graphical representation of the hourly passenger volume required to support a given system at a specified fare and headway configuration. They present a visual display of the service areas of each transit mode as well as the overlap in operational capabilities.

The construction of these envelopes and the transit systems for which they are developed are discussed in the following section. The resulting graphs are presented in Section III as are the results of an attempt to compare these systems on the basis of level of service. The conclusions and recommendations are presented in Section IV.

II. ANALYSIS OF OPERATIONAL DATA

Monorails, like other transit systems, can either be used for collection and distribution of passengers or in a line haul mode. Collection and distribution routes are characterized by frequent stops, low speeds, and short passenger trips or numerous transfers. Line haul or primary transit routes, on the other hand, are characterized by high speeds, high capacity, longer passenger trips and greater distances between stops. It is that segment of public transit; "particularly directed toward alleviating peak-hour loadings on major highway facilities and reducing parking demand in major activity centers." (2)

The types of transit systems of interest for this comparison are those that either do or can serve a primary transit or line haul function. They include; monorails, rapid rail, light rail and bus systems using restricted use lanes.

MONORAILS

The transit monorail system used for purposes of comparison is the Hatachi-Alweg, straddle system located in Tokyo, Japan. This line began operation in 1964 to service the demand from downtown Tokyo to Haneda airport, 8.2 miles away. (4) Additional information concerning this system and other comparable monorail systems is included in Appendix A.

RAPID RAILS

Rapid rail systems operate on dual rails with electrical propulsion on exclusive right-of-ways. Vehicle power pickup is usually by means of a 3rd rail.

Examples of more recent rapid rail systems are those of Washington-Metro and San Francisco-BART. Some of the older systems include; Philadelphia-SEPTRA, Chicago-CTA, Cleveland-SHAKER, and Boston-MBTA.

LIGHT RAILS

Light rail systems are defined as those that use: "predominately reserved, but not necessarily grade-separated, rights-of-way." (2) They are electrically propelled with power beings supplied through poles or pantographs from overhead wires. Examples of light rail systems include the Cleveland-SHAKER, Philadelphia-NORRISTOWN, and the Edmonton-NORTHEAST lines.

BUSWAYS

Busways are those operations in mixed traffic on freeways for the line haul portion of their trips. They may be provided with preferential access and lanes. Although there are many examples of this type of operation, an average or composite of these systems will be used for comparison.

SERVICE ENVELOPE METHOD

The method used to compare the operational characteristics and costs of these systems is a modification of a transit service model developed by Rea and Miller (5). This model produces a service-specification which: "defines the boundaries within which an operator is able to specify transit service for a given technology in predefined circumstances. An envelope is defined on one side by an economic or "viability" boundary and on the other by a "capacity" boundary. The basis for comparison is the location of the service-specification envelope in an output space defined by axes representing passenger flow and level of service." Level of service in the present use of this concept of presentation is represented by trip time, whereas Rea and Miller used or metric of velocity, net speed. Trip time, of course, reflects only one quality of the service provided, consequently an attempt was made to assess quality in a more general way. The method used for this assessment is discussed at the end of this section.

The service-specification envelopes are based on functions of capacity Flow Limits, Viability Flow Limits, and Trip Time. The necessary equations and the variables included in these functions are presented below:

[1] $$\text{Capacity Flow Limit} = (1+SPC)VSC \times NVT \times (60/HDWY)$$

[2] $$\text{Viability Flow Limit} = CPM(60/HDWY)\,/AFPM$$

where

SPC = ratio of standees to vehicular seating capacity

VSC = vehicle seating capacity

NVT - number of vehicles in train

HDWY = headway, minutes

CPM - operational cost per vehicle mile, dollars

AFPM = average fare per mile, dollars

[3] $$\text{Net Speed} = \frac{ATD}{\frac{ADBS}{MV} + \frac{MV}{ACC} \quad NLAT + (NLAT-1)\ DWELL + \frac{HDWY}{2}}$$

where:

ADT = average trip distance, feet

ADBS = average distance between stops, feet

MV = maximum velocity, feet/sec

ACC = average operational acceleration and deceleration, feet/sec/sec

NLAT = number of stops

DWELL= average dwell time at stops, minutes

HDWY = headway, minutes

[4] Trip Time, a deviation of Net Speed $= \frac{88\ ATD}{NET\ SPEED}$

The workings of these equations and the envelopes they produce are best demonstrated by example. The operational data from the Tokyo-Haneda monorail line will be used for this purpose. Using an average trip length of 7 miles with stations spaced at one mile intervals, maximum passenger capacities and average trip times were computed for headways ranging from a train every two minutes to one every 30 minutes, in one minute increments. The minimum passenger loads required for the line to pay for its operational cost was computed using a fare estimate of five cents per mile per passenger. These data were entered into a microcomputer to produce the data given in Table 3. A list of the program statements used to generate the data is presented in Appendix B.

The information presented in Table 3 indicates that when headways are as low as two minutes, a six car monorail train requires a minimum of 7818 passengers per hour to break even. That figures is based on each passenger paying five cents a mile for seven miles or 35 cents per trip. The passenger capacity available with two minute headways is 22,896 passengers per hour. This leaves an excess revenue potential based on 15,078 passengers per hour.

At two trains per hour or 30 minutes headways, 521 passengers per hour are required to support the system. This level of operation allows a

Table 3 TOKYO MONORAIL SERVICE ENVELOPE DATA

HEADWAY	LOWER LIMIT	UPPER LIMIT	NET SPEED	AVG TRIP TIME
2	7818	22996	43.8655	14.0429
3	5212	15264	42.3574	14.5429
4	3909	11448	40.9495	15.0429
5	3127.2	9158.4	39.6322	15.5429
6	2606	7632	38.397	16.0429
7	2233.71	6541.71	37.2365	16.5429
8	1954.5	5724	36.144	17.0429
9	1737.33	5088	35.1139	17.5429
10	1563.6	4579.2	34.1408	18.0429
11	1421.45	4162.91	33.2202	18.5429
12	1303	3816	32.348	19.0429
13	1202.77	3522.46	31.5204	19.5429
14	1116.86	3270.86	30.734	20.0429
15	1042.4	3052.8	29.986	20.5429
16	977.25	2862	29.2735	21.0429
17	919.765	2693.65	28.5941	21.5429
18	868.667	2544	27.9455	22.0429
19	822.948	2410.11	27.3257	22.5429
20	781.8	2289.6	26.7327	23.0429
21	744.572	2180.57	26.165	23.5429
22	710.727	2081.45	25.6208	24.0429
23	679.826	1990.96	25.0989	24.5429
24	651.5	1908	24.5978	25.0429
25	625.44	1831.68	24.1163	25.5429
26	601.385	1761.23	23.6533	26.0429
27	579.111	1696	23.2077	26.5429
28	558.429	1635.43	22.7786	27.0429
29	539.172	1579.03	22.3651	27.5429
30	521.2	1526.4	21.9663	28.0429

```
SPC= 1.12          VSC= 60          NVT= 6           CPM= 13.03
AFPM= .05          ATD= 7           ADBS= 1          MV= 72.9
ACC= 3.28          NLAT= 7          DWELL= 20        MINHDWY= 2
MAXHDWY= 30        HDWYINT= 1
```

maximum capacity of 1526 passengers per hour. Average trip time for the 30 minute headway case is 28 minutes. This includes average waiting period of 15 minutes and a 13 minute travel time. As the headways between trains decrease, the waiting times decrease correspondingly. The waiting time is always estimated by one half of the headway value.

A semilog graphical presentation of the service specification envelopes resulting from a plot of these values is presented in Figure 1. In these graphs, trip time is plotted on a linear scale of time in minutes, and passengers per hour on a logarithmic scale. The viability limit or break-even hourly passenger requirement defines the left boundary for the headway range considered. The right boundary is the maximum hourly passenger capacity. The graph in Figure 2 shows how the boundary would be affected by increases or decreases in focus. Fewer passengers, for example would be required if the fare was increased. This would have the effect of moving the viability limit to the left.

The effect of a change in the acceleration, deceleration or maximum velocity capabilities of the transit technology considered would have the effect of shifting the bottom line and top line location (See Figure 3). Assuming that trip length and station spacing remain fixed, a decrease in maximum velocity would lower the top and bottom lines representing an increase in travel time for all headways. In other words, the whole envelope would shift up for an increase in speed parameters and down for a decrease.

Using this approach, operational data was compiled for various examples of new rapid rail, old rapid rail, and light rail transit systems. In order to obtain representative data for generic forms of these modes, values

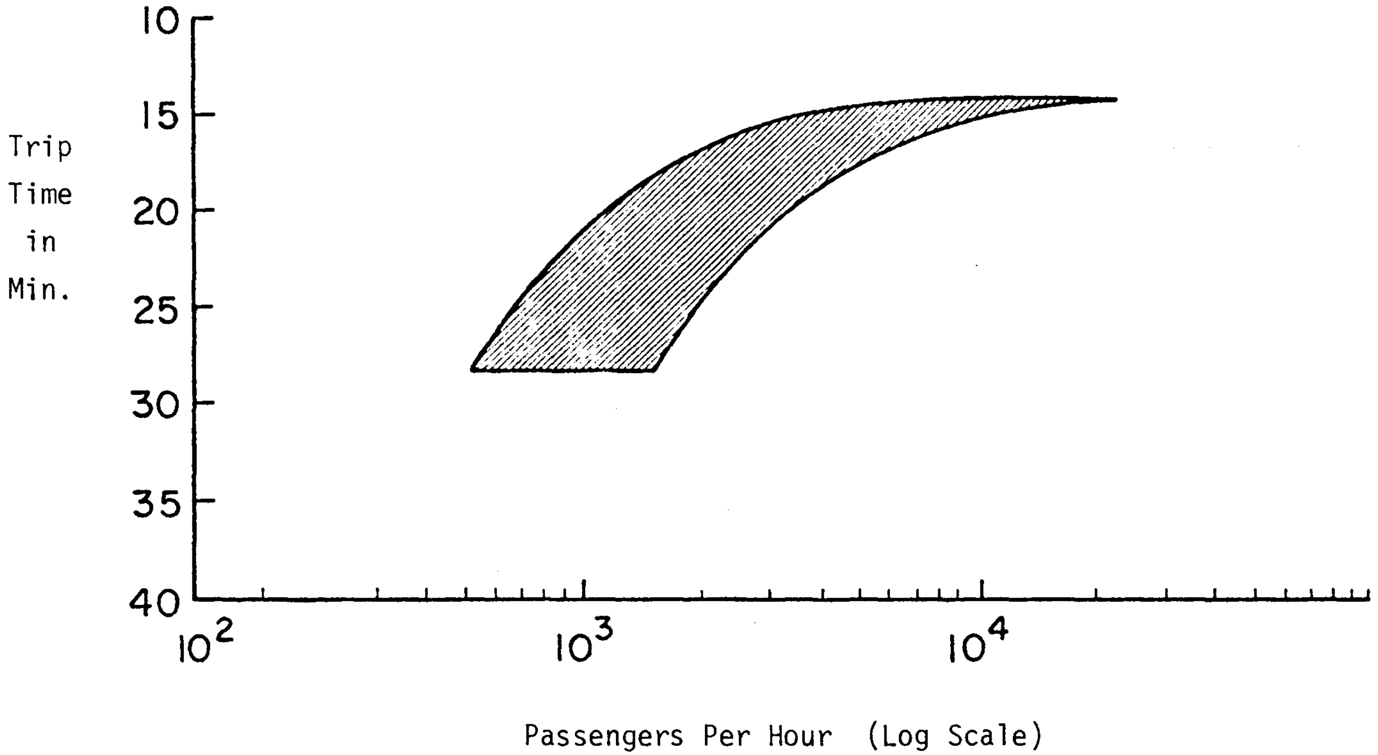

Figure 1. Service Specification Envelope for The Tokyo - Haneda Monorail Line.

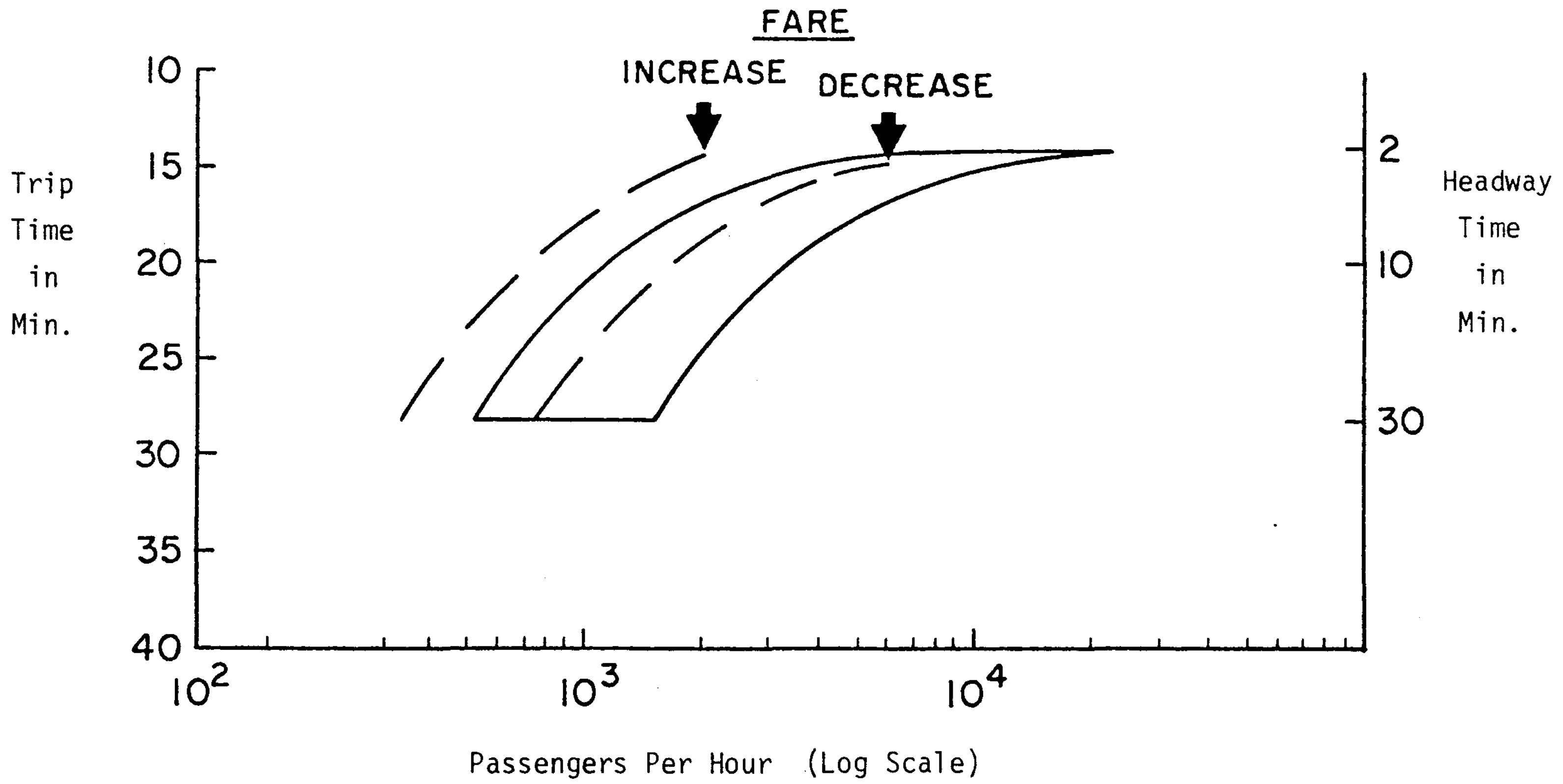

Figure 2. Effects of Fare Changes on Service Specification Envelope.

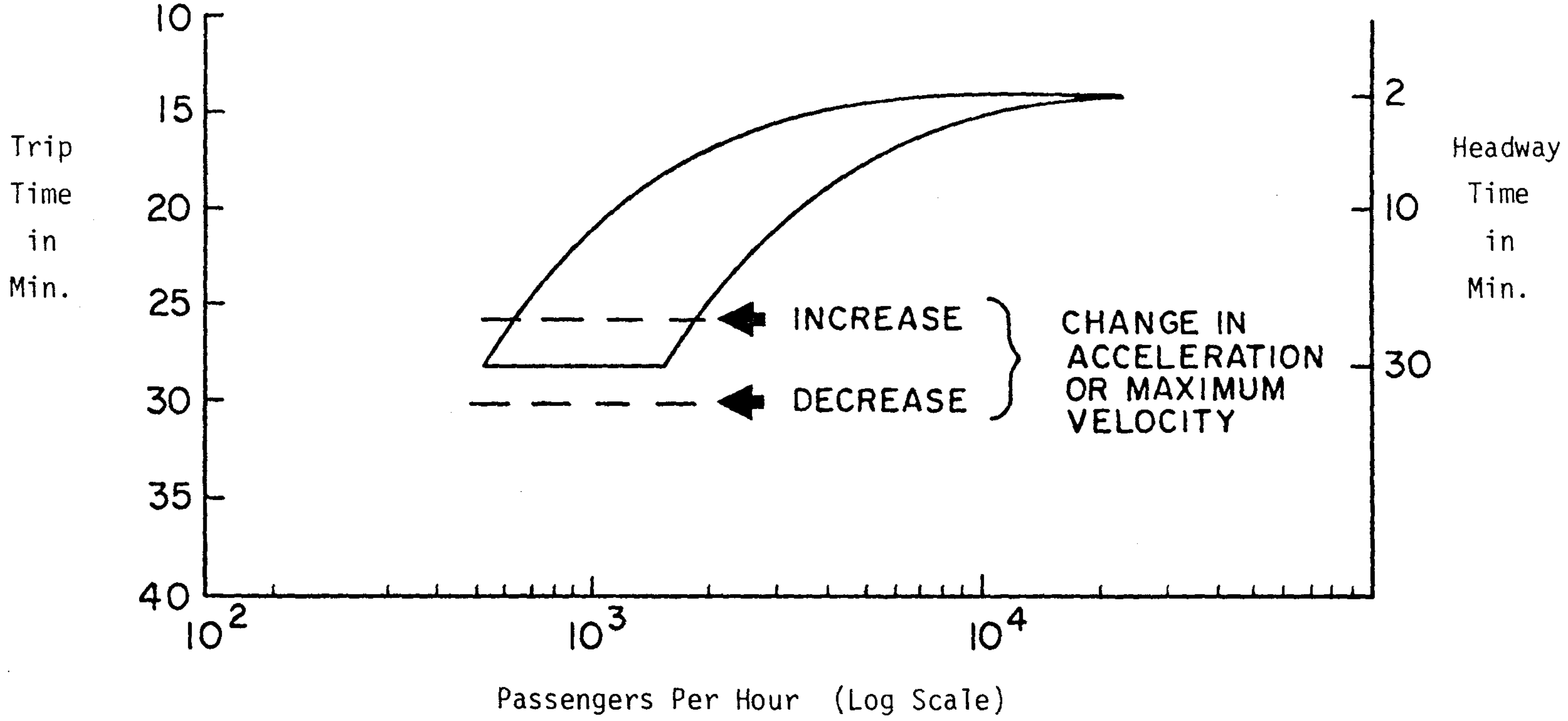

Figure 3. Effects of Change in Speed Parameters on Service Envelope.

for the specific examples were averaged. These data are presented in Tables 4, 5, and 6. Table 6 includes data for the operational characteristic of an average busway. These data were obtained from a source that had already derived average operational data. (2)

Once again using an average trip length of seven miles with stations at one mile intervals, service-specification envelopes were generated for mode averages, producing upper and lower passenger capacity limits and trip times over the headway range of two to 30 minutes. These data are presented in Tables 7 through 10. Data for the individual lines, as well as some samples of light rail and busway data with three mile trip lengths and quarter mile station spacing are included as Appendix C.

LEVEL OF SERVICE RATING FOR TRANSIT SYSTEMS

A possible alternative to the single-factor trip time criterion for transit system comparisons is a Level-of-Service (LOS) rating. This concept, taken from a similar (and familiar) system of ratings for highway facilities, as set forth in the Highway Capacity Manual (6), has been studied by a number of researchers, perhaps most recently by Bullard and Christiansen (7). LOS is therein defined as the "system's ability to provide reasonable travel times and a comfortable ride." The LOS concept is attractive because it is a multi-factor composite rating, essentially a (weighted linear equation, which can take in various aspects of the transit service as perceived by the would be user. In the original formulation, these factors (all rated on an alpha scale from A to F) were:

TABLE 4

Variable	Monorail Tokyo-Haneda	New Rapid Rail Washington	BART	Average
Standees to Seating Capacity	1.12	2.41	2.08	2.245
Seating Capacity	60	68	72	70
No. Vehicles in Train	6	6	6	6
Cost/Mile	13.03	27.3	23.94	25.62
Average Fare/Mile	.05	.05	.05	.05
Average Trip Distance	7	7	7	7
Average Distance Between Stops	1	1	1	1
Maximum Velocity	72.9	110	117.33	113.665
Average Operational Acceleration/ Deceleration	3.28	4.4	4.4	4.4
No. of Transfers in Average Trip	7	7	7	7
Dwell	20	20	20	20
Minimum Headway	2	2	2	2
Maximum Headway	30	30	30	30
Interval	1	1	1	1

TABLE 5

Variable	Old Rapid Rail Philadelphia SEPTRA	Chicago CTA	Cleveland GCTA	Boston MBTA	Average
Standees to Seating Capacity	2.73	2.06	.75	2.73	2.0675
Seating Capacity	67	49	80	64	65
No. Vehicles in Train	6	6	6	6	6
Cost/Mile	18.48	15.66	12.72	53.1	24.99
Average Fare/Mile	.05	.05	.05	.05	.05
Average Trip Distance	7	7	7	7	7
Average Distance Between Stops	1	1	1	1	1
Maximum Velocity	73.33	80.66	88	65.55	76.885
Average Operational Acceleration/ Deceleration	4.4	2.2	2.88	3.85	3.3325
No. of Transfers in Average Trip	7	7	7	7	7
Dwell	20	20	20	20	20
Minimum Headway	2	2	2	2	2
Maximum Headway	30	30	30	30	30
Interval	1	1	1	1	1

TABLE 6

Variable	Light Rail				Bus
	Cleveland Shaker	Philadelphia Norristown	Edmonton North East	Average	Average
Standees to Seating Capacity	1.41	1.64	1.53	1.527	1.92
Seating Capacity	49	84	64	65.67	26
No. Vehicles in Train	1	1	1	1	1
Cost/Mile	2.9	4.04	7.1	4.68	2.98
Average Fare/Mile	.05	.05	.05	.05	.05
Average Trip Distance	7	7	7	7	7
Average Distance Between Stops	1	1	1	1	1
Maximum Velocity	50	55	50	51.667	55
Average Operational Acceleration/Deceleration	3.1	3.15	2.45	2.9	2.5
No. of Transfers in Average Trip	7	7	7	7	7
Dwell	20	20	20	20	20
Minimum Headway	2	2	2	2	2
Maximum Headway	30	30	30	30	30
Interval	1	1	1	1	1

Table 7 NEW RAPID RAIL (AVERAGE) SERVICE ENVELOPE DATA

HEADWAY	LOWER LIMIT	UPPER LIMIT	NET SPEED	AVG TRIP TIME
2	15372	40887	53.8778	11.4333
3	10248	27258	51.6204	11.9333
4	7686	20443.5	49.5445	12.4333
5	6148.8	16354.8	47.6291	12.9333
6	5124	13629	45.8563	13.4333
7	4392	11682	44.2107	13.9333
8	3843	10221.8	42.6791	14.4333
9	3416	9086	41.2502	14.9333
10	3074.4	8177.4	39.9137	15.4333
11	2794.91	7434	38.6612	15.9333
12	2562	6814.5	37.4849	16.4333
13	2364.92	6290.31	36.3781	16.9333
14	2196	5841	35.3347	17.4333
15	2049.6	5451.6	34.3495	17.9333
16	1921.5	5110.88	33.4178	18.4333
17	1808.47	4810.24	32.5353	18.9333
18	1708	4543	31.6982	19.4333
19	1618.11	4303.9	30.9031	19.9333
20	1537.2	4088.7	30.1469	20.4333
21	1464	3894	29.4268	20.9333
22	1397.45	3717	28.7404	21.4333
23	1336.7	3555.39	28.0852	21.9333
24	1281	3407.25	27.4592	22.4333
25	1229.76	3270.96	26.8605	22.9333
26	1182.46	3145.15	26.2874	23.4333
27	1138.67	3028.67	25.7382	23.9333
28	1098	2920.5	25.2115	24.4333
29	1060.14	2819.79	24.7059	24.9333
30	1024.8	2725.8	24.2202	25.4333

Table 8 OLD RAPID RAIL (AVERAGE) SERVICE ENVELOPE DATA

HEADWAY	LOWER LIMIT	UPPER LIMIT	NET SPEED	AVG TRIP TIME
2	14994	35889.8	44.9516	13.7036
3	9996	23926.5	43.3692	14.2036
4	7497	17944.9	41.8945	14.7036
5	5997.6	14355.9	40.5167	15.2036
6	4998	11963.3	39.2266	15.7036
7	4284	10254.2	38.0162	16.2036
8	3748.5	8972.44	36.8782	16.7036
9	3332	7975.5	35.8064	17.2036
10	2998.8	7177.95	34.7952	17.7036
11	2726.18	6525.41	33.8394	18.2036
12	2499	5981.63	32.9348	18.7036
13	2306.77	5521.5	32.0773	19.2036
14	2142	5127.11	31.2633	19.7036
15	1999.2	4785.3	30.4896	20.2036
16	1874.25	4486.22	29.7533	20.7036
17	1764	4222.32	29.0517	21.2036
18	1666	3987.75	28.3824	21.7036
19	1578.32	3777.87	27.7432	22.2036
20	1499.4	3588.98	27.1322	22.7036
21	1428	3418.07	26.5476	23.2036
22	1363.09	3262.7	25.9876	23.7036
23	1303.83	3120.85	25.4507	24.2036
24	1249.5	2990.81	24.9356	24.7036
25	1199.52	2871.18	24.4409	25.2036
26	1153.38	2760.75	23.9655	25.7036
27	1110.67	2658.5	23.5082	26.2036
28	1071	2563.55	23.068	26.7036
29	1034.07	2475.16	22.6441	27.2036
30	999.6	2392.65	22.2354	27.7036

Table 9 LIGHT RAIL (AVERAGE) SERVICE ENVELOPE DATA

HEADWAY	LOWER LIMIT	UPPER LIMIT	NET SPEED	AVG TRIP TIME
2	2808	4978.44	19.7908	13.3396
3	1872	3318.96	19.0758	13.8396
4	1404	2489.22	18.4106	14.3396
5	1123.2	1991.38	17.7903	14.8396
6	936	1659.48	17.2104	15.3396
7	802.286	1422.41	16.6671	15.8396
8	702	1244.61	16.1571	16.3396
9	624	1106.32	15.6774	16.8396
10	561.6	995.689	15.2253	17.3396
11	510.545	905.171	14.7986	17.8396
12	468	829.741	14.3951	18.3396
13	432	765.914	14.0131	18.8396
14	401.143	711.206	13.6508	19.3396
15	374.4	663.792	13.3068	19.8396
16	351	622.305	12.9796	20.3396
17	330.353	585.699	12.6682	20.8396
18	312	553.16	12.3714	21.3396
19	295.579	524.047	12.0882	21.8396
20	280.8	497.844	11.8176	22.3396
21	267.429	474.137	11.5589	22.8396
22	255.273	452.586	11.3113	23.3396
23	244.174	432.908	11.074	23.8396
24	234	414.87	10.8465	24.3396
25	224.64	398.275	10.6282	24.8396
26	216	382.957	10.4185	25.3396
27	208	368.774	10.2169	25.8396
28	200.571	355.603	10.0229	26.3396
29	193.655	343.341	9.83623	26.8396
30	187.2	331.896	9.65634	27.3396

Table 10 BUS (AVERAGE) SERVICE ENVELOPE DATA

HEADWAY	LOWER LIMIT	UPPER LIMIT	NET SPEED	AVG TRIP TIME
2	1788	2277.6	19.0385	13.8667
3	1192	1518.4	18.3759	14.3667
4	894	1138.8	17.7578	14.8667
5	715.2	911.04	17.18	15.3667
6	596	759.2	16.6387	15.8667
7	510.857	650.743	16.1303	16.3667
8	447	569.4	15.6522	16.8667
9	397.333	506.133	15.2015	17.3667
10	357.6	455.52	14.7761	17.8667
11	325.091	414.109	14.3739	18.3667
12	298	379.6	13.9929	18.8667
13	275.077	350.4	13.6317	19.3667
14	255.429	325.371	13.2886	19.8667
15	238.4	303.68	12.9624	20.3667
16	223.5	284.7	12.6518	20.8667
17	210.353	267.953	12.3557	21.3667
18	198.667	253.067	12.0732	21.8667
19	188.211	239.747	11.8033	22.3667
20	178.8	227.76	11.5452	22.8667
21	170.286	216.914	11.2981	23.3667
22	162.545	207.055	11.0615	23.8667
23	155.478	198.052	10.8345	24.3667
24	149	189.8	10.6166	24.8667
25	143.04	182.208	10.4074	25.3667
26	137.538	175.2	10.2062	25.8667
27	132.444	168.711	10.0126	26.3667
28	127.714	162.686	9.8263	26.8667
29	123.31	157.076	9.64677	27.3667
30	119.2	151.84	9.47368	27.8667

(1) Accessibility --relates the alpha scale to time and distance, either walking or riding, to or from the station.

(2) Travel Time --this is a ratio of transit time on a typical trip to the time it would take to make the same trip by car. This ratio is then associated with the alpha scale.

(3) Directness of Service --number of transfers necessary to accomplish a trip, the less, the higher the rating.

(4) Delay --a rating of the amount of time expended in unexpected delay during a trip (which may or not be made up by higher travel speeds after the delay)

(5) Frequency of Service --the "policy" or maximum time between consists or units of the transit system. This is often called "headway."

(6) Reliability --an estimate of how well the system sticks to its schedule, with adjustments for frequency of consists or headway. The more the headway, the less desirable late trains or cars are.

(7) Passenger Density --this factor supports the generally accepted user perception that it is much more desirable to sit than to stand, even for short trips. The rating is arrived at by computing a ratio of passengers being carried to seating capacity, and also brings in the type of seating provided.

(8) Passenger Comfort --three factors:

(a) Acceleration/deceleration capability

A = less than 1 fps/s
to
F = greater than 4 fps/s

(b) Temperature (high and low extremes)

(c) Noise A = less than 60 dB
to
F = greater than 95 dB

These ten factors, thus rated on an alpha scale, are converted to an equal-appearing (Likert) scale ranging from 5 (A) down to 0 (F). Bullard and Christiansen then conducted a survey of transit users to derive weights for each of these factors. The final composite rating of LOS is as follows:

$$[5] \quad LOS = \frac{(10f1)+(10f2)+(10f3)+(5f4)+(15f5)+(15f6)+(15f7)+(5f8a)+(10f8b)+(5F8c)}{100}$$

This rating scheme is well-suited to evaluation of a transit system in a specific locale. Since several factors are site specific, they are not particularly suited for comparison of transit modes which are not only different in design or mode, but also are located in different places. These factors are (1) Accessibility, and (2) Travel Time.

Another factor not well-suited for the present purposes of this study of monorail technology vs. other types of rail transit systems is (4) Delay, which really refers to traffic conditions that might impede a bus, but is not applicable to a dedicated right-of-way system. In fact, it is well to point out that the Bullard-Christiansen rating for LOS was developed for bus systems specifically.

Table 11 identifies the modifications that must be made to the LOS rating to make it suitable for the present study, and provides the modified

Table 11. MODIFIED L-O-S

Rating Scheme for Monorail Study

1. ACCESSIBILITY - No data available for systems studied, drop factor.
2. TRAVEL TIME - No data on auto travel time over route equivalent to transit route, drop factor.
3. DIRECTNESS OF SERVICE - Transfers required on given trip; can be roughly estimated. Retain Factor.
4. DELAY - No data on actual trip delays vs. scheduled, not completely applicable to dedicated right-of-way facility. Drop Factor.
5. FREQUENCY OF SERVICE - Policy headway evaluated for peak and off-peak. Retain Factor.
6. RELIABILITY - No data on schedule maintenance, drop factor.
7. PASSENGER DENSITY - Occupancy/seated capacity ratio, data available, retain factor.
8. PASSENGER COMFORT (A) - JOLTING - Acceleration and deceleration capability data available, retain factor.
    8. (B) TEMPERATURE - No data, drop factor.
    8. (C) NOISE - Rough estimate of noise available, retain factor.

Modified L-O-S rating for Monorail Study:

$$LOS = 10f_3 + 15f_5 + 15f_7 + 5f_{8_A} + 5f_{8_C}$$

composite rating equation.

In order to compare LOS ratings with Trip Time ratings (which are unidimensional average speed of transit estimates), four representative transit systems were evaluated with respect to the five factors identified in Table 11, using the guidelines established by Bullard and Christiansen (8). These four transit systems were:

(1) Monorail in Tokyo, Japan

(2) Rapid Rail System, the Metro in Washington, D.C.

(3) A light rail (trolley) system with some dedicated right-of-way in Cleveland, Ohio

(4) A park-and-ride conventional bus system using HOV access to downtown in Dallas, Texas.

III. RESULTS OF OPERATIONAL COMPARISONS

The service-specification envelopes for the average operational data are presented in graphical form in Figure 4. The envelope for the older rapid rail systems is not included in this figure because of its similarity to that of the newer systems. It is included, as are the envelopes for light rail and bus averages using 3 mile trip lengths and quarter mile station spacings, as Appendix D.

The graphs in Figure 4 shows an increasing trend in both break-even or viability capacity and maximum capacity limits starting with busway operations on the lower end to rapid rail on the upper end of the spectrum. The difference in trip times among the various modes is not as pronounced. The four transit modes considered are so similar in their speed parameters that the differences in trip times is of no practical consequence.

Level of Service (LOS) rating which was intended to add a measure of discrimination to the trip time criterion failed to demonstrate such discrimination. The outcome of this comparison is presented in Table 12. It will be noted that all of these modes earn relatively poor "C" marks on an alpha scale of A to F, since LOS includes on factor 7, passenger density (weight of 15). All but the under-utilized Dallas bus system have standees during peak operations. If this factor is discounted, and the divisor for the overall LOS rating is reduced from 50 to 35, the final column in Table 12 results. Buses show up as inferior to other modes,

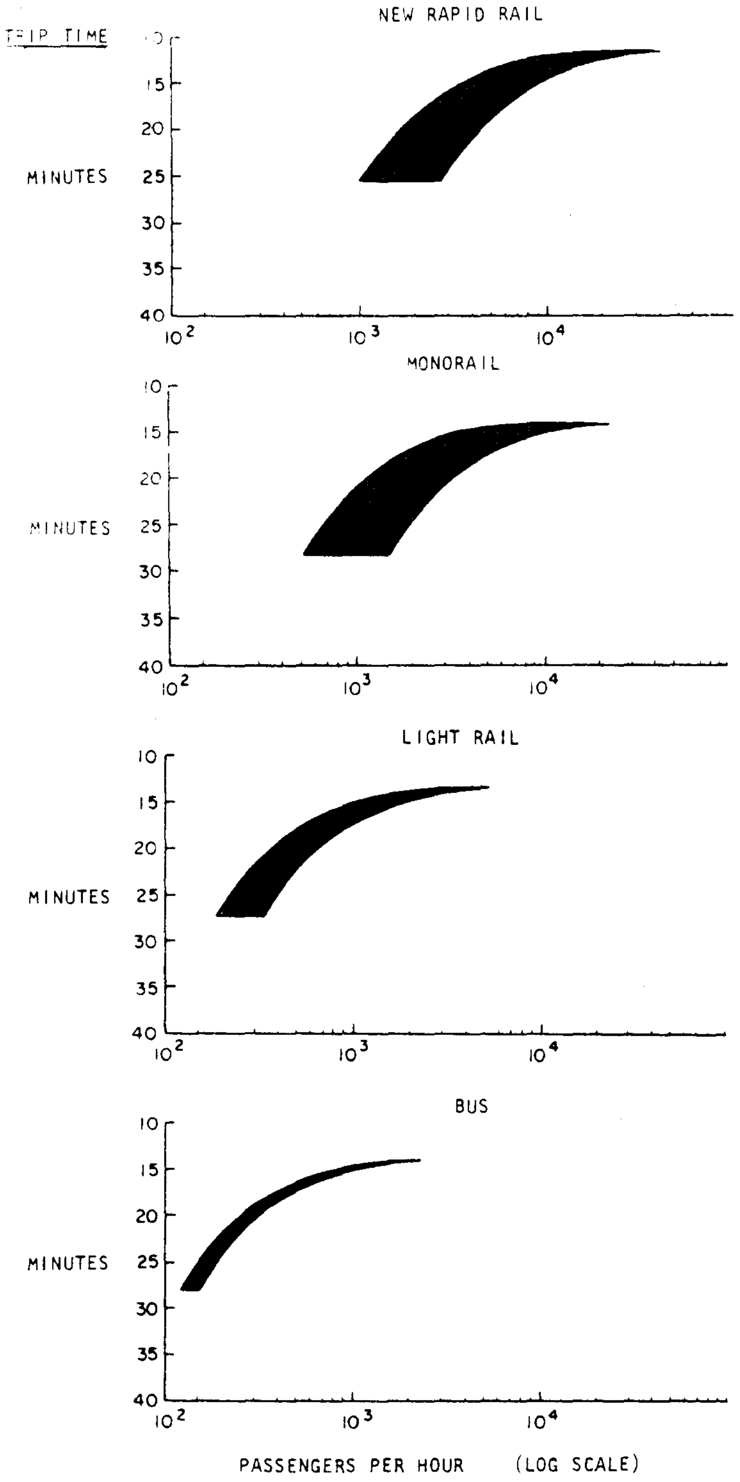

Figure 4. Service Specification Envelopes for Four Modes of Transit

Table 12 LOS RATINGS FOR COMPARABLE MASS TRANSIT MODES

RATING FACTORS

TRANSIT SYSTEM	Directions of Service (F3) Weight: 10		Freq. of Service (F5) Weight: 15		Passenger Density (F7) Weight: 15		Accel/ Decel (F8A) Weight: 5		Noise (F8C) Weight: 5		LOS Rating	LOS Rating Without F7
	Rating	Weighted	R	W	R	W	R	W	R	W		
RAPID RAIL- WASH. DC METRO	B	40	A	75	F	0	D	10	B	20	2.9=C	4.14=B
MONORAIL-TOKYO	B	40	A	75	F	0	F	0	C	15	2.6=C	3.71=B
LIGHT RAIL- CLEVELAND SHAKER	D	20	A	75	F	0	D	10	B	20	2.5=C	3.57=B
BUS-PARK & RIDE DALLAS	D	20	B	60	B	60	F	0	C	15	3.1=C	2.71=C

VALUE OF
ALPHA RATINGS:

A = 5
B = 4
C = 3
D = 2
E = 1
F = 0

but PCC* trolleys, a modern rapid rail system that is probably the most costly of its kind in the world, and a 19-year old monorail system in Tokyo rate the same - B. Presumably, if these four factors represent the non-site-specific point of view of the user, these 3 systems would be equally satisfactory to the same person. Obviously LOS as modified here is not a very sensitive discriminator.

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*President's Commission Car, a technical group in the 1930's appointed by the President of the U.S. drew up specifications for this design.

IV. CONCLUSIONS AND RECOMMENDATIONS

The service specification envelope approach indicated a continuum of hourly passenger requirements with some overlap in capabilities. Busway and light rail systems tend to group at the lower end of this continuum, meaning that they require fewer passengers per hour to break even but have smaller maximum capacities. Monorail and rapid rail cluster at the upper end of the continuum with considerable overlap in their operational envelopes. They cost more to operate but provide greater maximum capacities.

The trip time dimension of the various systems showed only slight differences in capabilities and did not practically discriminate. The Level of Service comparisons also failed to show any significant differences in this dimension. Based on these comparisons it was concluded that monorail transit technology has operational characteristics that fall between those of light rail and rapid rail but performing a great deal like the latter.

The service-specification envelope methodology served the purpose for which it was intended. It allowed a visual comparison to be made of the operational characteristic of the various systems which is an improvement over the presentation of individual data points.

Monorails are a proven transit technology similar in operation to rapid rail systems. Due to the nature of their smaller, above ground construction, they are less costly to build than other underground or elevated rapid rail systems. Use of pre-casting construction techniques allow monorail systems to build quickly with little disruption of traffic or commerce.

The line switching constraints of 8 to 30 seconds do not pose any difficulty considering the minimum train headways used in practical transit operations (1.5-2 minutes). Safety and emergency egress can be handled by using trains on the parallel beamway or pneumatic slides similar to those used in aircraft. These provisions are available even though monorail systems have excellent safety and reliability records.

This background along with the information and experience in the performance of the first two tasks allows the following recommendations to be made:

1. Monorail systems are a viable transit technology and as such should be seriously considered as an alternative to other transit modes.
2. Transit modes alternative analyses can only provide a preliminary examination of the feasibility of the various systems. As a result, in most cases, all alternatives are feasible. Need or passenger demand, cost, capitalization methods, political climate, and other factors ultimately determine the selection of a mode. Consequently, the time and resources committed to investigating alternatives would be better spent on requesting bids from vendors or various suppliers for systems to perform specific functions.
3. Monorail systems are eminently feasible in any city where demands warrant the consideration of rapid or light rail. Since this is the case and since the present investigators are not in a position to make an engineering and construction estimate to build a monorail or any other transit system, it is recommended that the third task of this project not be attempted and the project concluded at this point.

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