Considering Monorail Rapid Transit for North American Cities

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Cover Picture: Seattle Alweg Monorail built in 1962. Source: Seattle Times

INTRODUCTION

Monorails have often been lumped together with flying cars as part of a naïve, cartoonish vision of the future. Despite the immense popularity monorails have had with the general public, this form of transportation has been mainly relegated to world's fairs and amusement parks.

Recently, however, a number of major, transit-grade monorails have either been built or are in the construction or planning phase. Japan is clearly the leader in the construction of new monorail systems. The Kika-Kyushu, Chiba, Osaka and Tama monorails were launched in 1985, 1988, 1990 and 1998 respectively and have a combined line length of about 50 kilometers and over 200,000 passengers per day with over a hundred more line kilometers planned. Two further monorails in Maihama(Tokyo) and Naha(Okinawa) will open within in the 2001-2003 timeframe. Kuala Lumpur, Malaysia will have its own inner-city monorail in 2002 fully built by a company started for that purpose. A further Malaysian monorail system is in development for the planned city, Putrajaya.

In the United States, a fully automated 4 mile long transit-grade monorail is under construction in Las Vegas, with a 4 mile extension in the planning stage. This monorail builds upon the success of an initial monorail shuttle between two major hotels. The initial line is privately funded and expected to reward investors with healthy returns. Finally, numerous monorail lines are under serious consideration in Seattle. Respected studies have shown them to be very competitive with light rail and bus semi-rapid transit alternatives.

In the course of this paper, we will examine whether these numerous recent developments are simply a "fad," or whether it just took monorail this long to earn serious respect, or whether major technical advances have improved monorails cost/benefit performance vis-à-vis other forms of urban transit?

Thus, by defining monorails and their basic components, exploring recent technological innovation in monorail transit and actual monorails in operation we can then proceed to answer the question of whether monorail rapid transit has a role to play in North American Cities, and if so, under what conditions?

PART ONE

Defining Monorail

The monorail society defines monorail as "A single rail serving as a track for passenger or freight vehicles. In most cases rail is elevated, but monorails can also run at grade, below grade or in subway tunnels. Vehicles are either suspended from or straddle a narrow guideway. Monorail vehicles are wider than the guideway that supports them." However, this rather straightforward definition is somewhat misleading as it downplays the wide range of technologies, operating principles and appearances the definition includes.

A. Monorail Types

- *Monorail (Schwebebahn)*

The first generally recognized monorail was the Schwebebahn ("swaying railroad") in Wuppertal, Germany. It is the only true "mono-rail." A single steel rail is suspended from an elevated structure along which a single rail runs. In this instance, the vehicle weight is both supported by the rail and guided by it. The position of the vehicle in respect to the rail is unlike traditional dual-rail systems but the basic technology by which the vehicle operates is no different from that of a railroad except that the wheels are double-flanged.

Figure 1.1-- Schwebebahn in Wuppertal, Germany (1901) Source: Alweg Archives

- *Suspended Monorail (Safege Type)*

Modern versions of the Schwebebahn look similar in that the monorail is suspended from above. However, instead of using a single rail for support and guidance, the single rail is replaced by a hollowed-out concrete or steel beam, and rubber tires are used instead of metal wheels. Although this is the most common configuration, numerous combinations of steel or concrete running surfaces and rubber tires or steel wheels—both singly and doubly flanged have been proposed.

Figure 1.2--Chiba, Japan "Townliner" Suspended Monorail. Source: The Monorail Society

- *Straddle Monorail*

The straddle monorail is by far the most common monorail type that has been put into operation. It is visually probably the most pleasing type and fits into urban environments better than suspended monorails which normally need to be taller to allow for the necessary vehicular clearance under the train. The straddle or sometimes "Pendulum" monorail is composed of a train running on a concrete or steel guideway. The train's load bearing tires run on top of the guideway beam while the guidance tires run along the two sides of the said beam. Proposals for high speed straddle monorails that use the straddle principle use slightly different configurations but the principle is roughly the same.

Figure 1.3--Seattle Alweg Monorail—Straddle Monorail (1962). Source: The Monorail Society

- *Cantilevered Monorail*

The cantilevered or side-straddle monorail is similar in appearance and operation to the straddle monorail. However, trains going in opposite directions can share a single (but rather large) beam since cantilevered monorails are balanced by wheels on surfaces found on the sides of beam. While several companies promote such monorails, they have not seen any applications as of yet.

Figure 1.4--Owen Transit cantilevered monorail. Source: The Monorail Society

- *Maglev Monorails*

Most maglev (short for "magnetic levitation") trains are essentially variations on the straddle monorail. Instead of on-board motors, the interaction of magnets on the vehicle and on the track moves the vehicle forward, while the vehicle itself is slightly levitated by other magnets. While maglev is an interesting technology, its complexity suggests that it is best suited to intercity rather than intra-city installations, placing it beyond the scope of this study. In addition, maglev monorail's dramatically different operating principles compared with other monorail types suggest that it serves little purpose to analyze maglev alongside more established monorails.

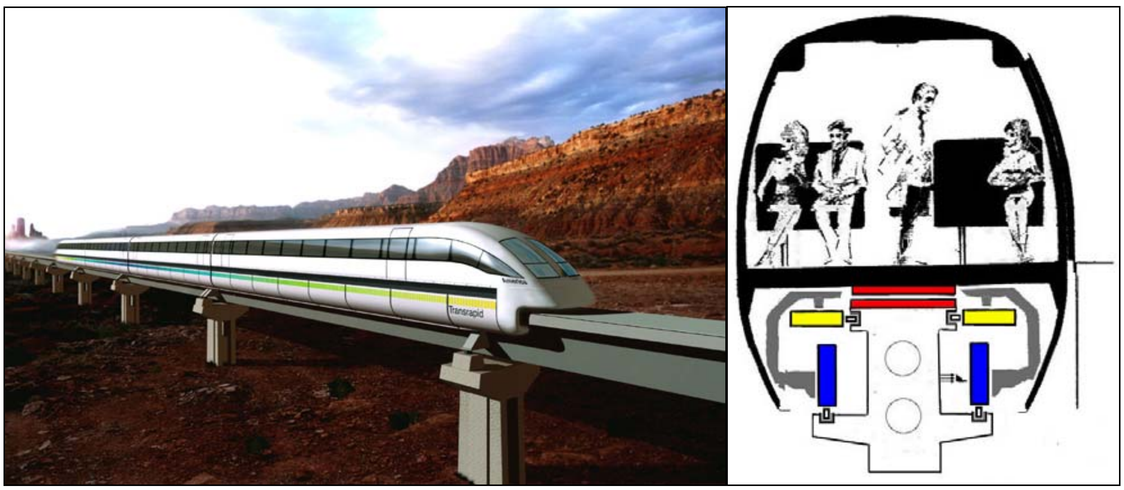

Figure 1.5--The Transrapid system (Right) and the Maglift system (Left), two of several levitating monorails. Source: Transrapid/Maglift.

B. Characteristics of Monorail Technology

ROW A—Grade Separated

Monorail operates solely on exclusive right-of–way. In this respect monorail operates as a "rapid transit" system. Monorails cannot operate in mixed traffic as buses or trams do, because the guideway beams cannot be crossed by other vehicular or pedestrian traffic at ground level unlike rail tracks which can be imbedded into the street. However monorail guideways placed on aerials allow for unhindered traffic flow below. Thus, monorail is served by stations most commonly elevated, but also underground or a few feet above ground level. Although stations require considerably more investment than simple street level light rail platforms, stations do add to the public "visibility" of the transit system. A station can also provide other services, like retail or snack bars that make public transportation a more pleasant and convenient method of travel.

- *Safety and Evacuation*

Monorails have been shown to be one of the very safest forms of transportation. Grade-separated operation generally rules out collisions with automobiles, trucks and pedestrians. The single fatal accident in the history of monorail operation after billions uneventful passengers, occurred when the Schwebebahn in Germany derailed after a wrench was left on the track; four people died. Since nearly all monorails built since the original Schwebebahn have not used a single rail as the term "mono-rail" would imply, and have instead used concrete guideways, derailment is extremely unlikely. The straddle-monorail, in particular, hugs the guideway in such a way to almost rule out such a possibility.

The fact that monorail is usually elevated poses some evacuation challenges. Suspended monorails usually have doors in the floor linked to stairs or a slide as on commercial aircraft. Japanese straddle monorail standards require fully articulated vehicles to allow longitudinal evacuation through the front and rear of the train onto a waiting train. The Malaysian system uses lateral evacuation to a waiting train on the guideway that supports trains in the other direction. Older American monorails use another train to push the stranded vehicle to the next station but when that is not possible, rescue via ladder from the ground is necessary. The Las Vegas monorail under construction provides an emergency walkway between dual monorail beams which is more in line with most rapid transit.

Monorails can be built to meet full seismic codes. In fact, monorails have a proven track record when it comes to earthquakes. The Seattle monorail withstood that region's 2001 Earthquake and the Osaka monorail the nearby Kobe Earthquake.

Rubber tired Traction and Guidance

With few exceptions, like the Schwebebahn, monorail systems use rubber tires for traction. Aside from the guideway, this is the main technological difference between monorail and traditional rail. While rubber traction on steel rails is found on at least one monorail system (Aerobus), most systems with rubber tires run on concrete surfaces. In this regard, most monorail vehicles run more like road vehicles than railway trains. To be sure, such rubber on concrete traction can be found on the Paris, Montreal and Sapporo Metros as well as on most AGT systems. There are both advantages and drawbacks to this method.

Figure 1.6—Two axle Rubber tired Hitachi monorail bogie. Source: Hitachi

- *Energy Consumption*

Energy consumption is somewhat higher with rubber tired traction. Rubber tires on concrete (as well as rubber tires on steel) have a greater rolling resistance and rotational inertia than steel on steel rail technology. Common rail operation tactics such as coasting can be much less utilized by monorails. Since energy consumption varies with the particular operating regime of a line, exact figures are not possible. However, an estimate of 25 to 30 percent greater energy consumption over rail technology is given

- *Acceleration and Breaking*

Rubber tired vehicles can achieve a much higher rate of acceleration and breaking than steel tired ones. For monorail systems, however, this is usually not a significant advantage since acceleration is limited much more by passenger comfort, especially by the passenger comfort of standing passengers. Also, high breaking rates are less necessary where exclusive right-of-way generally rules out collisions with street traffic, which happens to be the case for monorail.

- *Gradients*

Theoretically, rubber tired traction can overcome gradients of more than 15% whereas rail technology can not safely exceed 10%. In reality, steep gradients require very powerful motors and are uncomfortable for standing passengers. This means that rubber tired technologies do not have quite as strong an advantage over rail in this respect. In difficult alignments, however, monorail's climbing ability does stand out. An example of this is the Shonan suspended monorail in Japan, where 10 % gradients are found. And the authority responsible for designing Seattle's proposed system found that steeper gradients over water crossings would shorten bridges and thus lower bridge costs significantly.

- *Weather*

Rubber tired vehicles running on exposed surfaces, as with the straddle (but not with most suspended) monorail technology are much more susceptible to cold weather conditions (ice, snow) than rail. Under these conditions the guideway must be heated, entailing appreciable energy costs. The few suspended monorails built in the last few years, like the Chiba Monorail in Japan were primarily built because their running surfaces are enclosed and are thus protected from the elements.

- *Noise*

Rubber tired systems are generally quieter in sharp curves than the best rail technology. When rail maintenance is lacking or postponed, as is far too often the case, the benefit of rubber tires can be appreciable. In addition, both straddle and Safege-type monorail systems shield the tire noise unlike other rubber tired applications. Straddle monorails trains shield the tires since the train side stretches beneath the wheels to access the electric catenary, whereas Safege-type monorails have the wheels shielded within the guideway. Rubber tired vehicles produce much less vibration than vehicles with steel tires. Furthermore, since rubber tired monorails produce basically no electromagnetic "pollution", they can be run near hospitals and scientific institutes without concern.

Figure 1.7—Extremely quiet Walt Disney World straddle-type monorails glide into the Contemporary Resort atrium; guest rooms are directly above and shops directly below the trains. Source: Disney Co.

Operational Characteristics

- *Power*

Onboard electric motors power monorail vehicles. On a straddle-type monorail, trolley wires are suspended along the side of the guideway. A shoe behind the monorail skirt picks up electricity.

- *Speed*

Transit-grade monorails generally operate at maximum speeds of 60-90kph (40 to 55 mph), which is comparable to most applications of rail technology within urban areas. Average operating speed of monorails are comparable to subways due to the fact that they are likewise grade separated and use similar station spacing distances—generally in the range of 20 to 30 mph, very high for urban mass-transit.

- *Ride*

Monorails' ride is superior to cars and buses and similar to that of wielded rail. Suspension is usually provided by air-springs. Forces exerted in curves are reduced by banking the guideway slightly in straddle-systems. Suspended monorails can sway several degrees in curves, reducing forces. Both straddle and suspended monorails provide passengers with the sensation of smooth flight, especially since passenger's visual cues support the sensation.

- *Switching*

One of the most common misconceptions about monorails is that monorails do not, or cannot, employ switches. In reality, switching is extremely important to monorail operations. The Shonan suspended monorail in Japan employs switches at stations so that a single guideway between stations can be used for bi-directional operation. Even the Disney monorails which operate in a loop must have switches to move trains to and from the maintenance yard. There are a wide range of switches for different purposes. For example, the straddle-type Las Vegas monorail utilizes turnout, crossover and pivot switches in its operation. Due to the weight and size of concrete or steel beams, the switching is slower—roughly 15 seconds compared to 0.6 seconds for traditional rail. This increase in switching time would likely result in increased minimum headways over traditional rail if the switching is to be used regularly in line operation.

Figure 1.8--Switches in the Osaka Monorail maintenance facility.

- *Maintenance*

Concrete monorail guideways require extremely low maintenance. Rubber tires last for approximately 100,000 miles. Monorail vehicles have a long life span, similar to trains riding on rails (30 years or more), whereas buses have a recommended life span of only 10 or so years.

Conclusion

In general, Monorail technology is well suited to urban transit applications. It compares favorably to traditional rail technology on the whole. While monorails do have several significant disadvantages that cannot be outright dismissed—like somewhat higher energy costs (for rubber-tired systems) and slower switching as compared with similar rail systems, it is rare that these considerations would amount to a "fatal-flaw". In fact, these considerations should, more often than not, be minor in the general exercise of mass-transit planning. Indeed, it is in those very areas where monorail technology holds the advantage over steel-rail technology—most notably in its lower noise production and greater grade-climbing abilities—where monorail has the ability to make a fixed transit line feasible where it would not be otherwise.

PART TWO

Straddle Monorail Systems and Technology

As shown in Part one, the word "Monorail" describes a rather broad class of transit systems that use a single rail or beam for vehicle support and guidance. While numerous systems have been developed to one extent or another, and their technological underpinnings have been shown to be sound, only certain systems have been rigorously tested in operation. A serious consideration of monorail rapid transit for urban transit applications has to weigh the advantages and disadvantages of these successful systems. In nearly every case, these successful systems have been straddle monorails.

The straddle monorail has seen the most real world testing and service by far, primarily due to its ability to fit neatly into built up areas, with only minor visual blockage. The straddle monorail is probably the most mature monorail type and will likely remain so for some time.

Currently, transit-grade straddle monorail systems are manufactured by Hitachi of Japan, Bombardier of Canada and Monorail Malaysia of Malaysia. All transit-grade straddle monorails are descendents of the monorails of the now defunct German company, Alweg, which built the Seattle monorail for the 1962 world's fair. The Japanese conglomerate Hitachi bought the rights from Alweg to manufacture Straddle monorail systems. Hitachi is by far the most successful monorail manufacturer having built numerous systems and having invested heavily in the development and adaptation of the straddle monorail technology. Hitachi was to have built a monorail in Kuala Lumpur, but when the Asian financial crisis hit in the late nineties, Malaysia found the system to no longer be affordable. Instead, a local company, Monorail Malaysia was found to develop and construct the system cheaply by returning to the early Alweg specifications. The Canadian transportation giant, Bombardier, readapted the Walt Disney World Monorail for its transit-grade monorail, which is being built in Las Vegas and which has been proposed for numerous other American cities. Although, the Disney monorail is not a descendent of the Seattle monorail, it is a 5/8ths scale model of the Alweg demonstration train near Cologne, Germany Mr. Disney visited in the 1950's.

A. Aerial Structures

- *Guideway*

The most important structural element of a monorail system is the monorail guideway. The straddle monorail guideway is most often a concrete beam, occasionally a steel one. Each monorail beam acts as a small bridge; it must be built to support the load of the vehicle (including "live" loads like forces exerted when breaking) while not buckling under its own massive weight. In addition, the beam's design must take its guidance function into account, the beam and the vehicle must fit like a hand and a glove, so that the contact guidance wheels and the sides are maintained. The beam's width must also be wide enough so that the monorail train can be balanced given the small wheelbase. Logically, wider beams allow for wider vehicles, but wider beams also make for less aesthetically pleasing guideways. Unlike beam width, which is approximately ¼ the width of the monorail train due to center-of-gravity and riding quality concerns, beam height and length are relatively flexible as long as the structural integrity of the span is maintained.

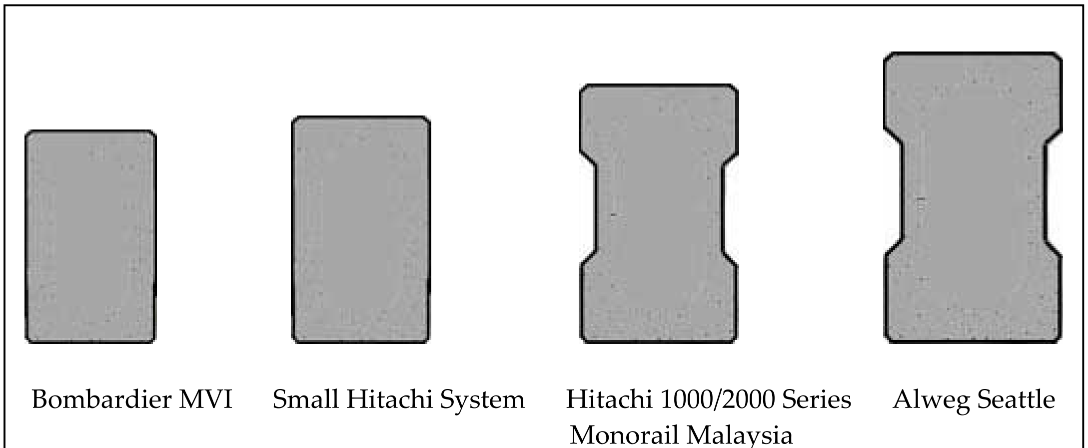

Figure 2.1—Relative Comparison of Guideway Beam Cross-sections. Source: The Monorail Society

Guideways are considerably more complex than their initial appearance may suggest. Straddle monorail guideways are designed in three dimensions. In a curve, the guideway beam bends not only on the horizontal plane but also banks in the vertical plain. The amount of bend is also dependent on the radius of the particular curve. To allow for this variation, concrete beams are formed individually in various molds with set radii, banking and spans. Transit-grade monorails have a minimum curve radius of about 40 meters. However, such a tight radius is generally avoided, since running tire slip angles and the forces on the guide tires mean that vehicles must operate at significantly reduced speeds.

Figure 2.2—Alignment of the Okinawa system through Naha city. Tight turning radii and a narrow crosshead profile mean that straddle monorails can be fitted into dense urban alignments. Source: Yui Rail

Modern developments in guideway design have been concerned with reducing the impact of the guideway on its surroundings because the relatively low visual and impact of the straddle monorail structure on urban environments is perhaps its greatest potential asset.

While the weight of the vehicle would seem to be the major determinant of guideway dimensions, weight is only a part of the picture. Gross axle loading of transit-class monorail vehicles are much comparable to most light rail and heavy rail rapid transit systems at 8 to 11 metric tons per axle. However, in spite of this, straddle monorail guideways are significantly less obtrusive than elevated rail, or AGT systems like the Vancouver Skytrain due to the distribution of the weight of the vehicle (not to mention the steel rails placed on top of those structures).

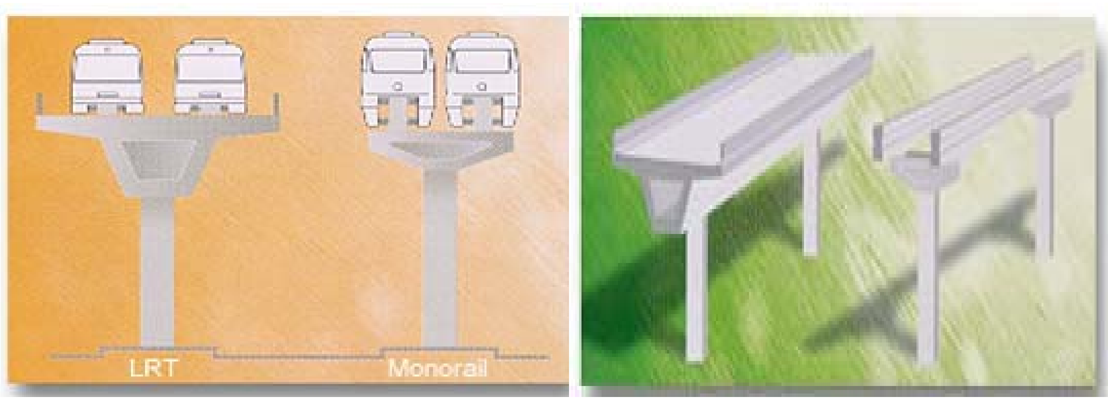

Figure 2.3—Comparison of large-type straddle-monorail with light rail aerials. Source: Monorail Malaysia.

A very effective way to reduce the visual impact of guideways and to allow longer spans (and thus fewer columns) is to use arched guideway beams, "haunched girders." This is one of the major positive developments in guideway design. Such beams allow longer spans, and decrease the visual impact of the beams especially at the center point. Furthermore, any visual impact is much more likely to be perceived positively given the gracefulness of the arched design.

Figure 2.4—Kuala Lumpur monorail guideway has both straight (foreground) and arched (background) segments. Source: Monorail Malaysia

- *Columns*

Columns are usually essential elements of a straddle monorail system. While guideways can run at ground level, or in a tunnel, the ability to use public right-of-way over streets requires that columns be used.

In general, column size and guideway length are inversely related to each other, with longer spans requiring less frequent but more massive columns, and shorter spans requiring frequent and lighter columns. While this may suggest many possible combinations, the matrix of column/guideway proportions in use is rather limited; a rough "golden" ratio based on visual appeal and the properties of concrete seems to exist. The agency responsible for designing Seattle's new monorail believes that current technology and good design sense makes 120 foot spans supported by 36 inch diameter, 30 foot tall columns ideal.

The column profile is another important element. Whereas most monorails in the past have used easy to cast square columns, the Seattle system is to have columns with a round base. They believe that rounded columns create a softer streetscape and allow for better sight lines. Another approach is to use rectangular columns. The short side of such a column would be visible to those on either side of the aerial, i.e. to those likely to be closest, while the long side is prominent only to observers standing directly under the guideway or looking further down the street. The bombardier system makes very good use of this approach. (Figure 2.6)

A third approach is to treat columns as sculptural elements. The proposed Hitachi design for Kuala Lumpur takes this approach. The graceful, rectangular but curved columns create an elegant colonnade. (Figure 2.6)

Where there is vehicular traffic under monorail guideways, the recommended minimum column height is approximately 5 meters. However, there is a trend towards using significantly taller columns in the range of 10 to 12 meters to reduce the visual impact of the guideway by placing it farther overhead. This approach also has a pleasant side-effect: it improves the view for monorail passengers.

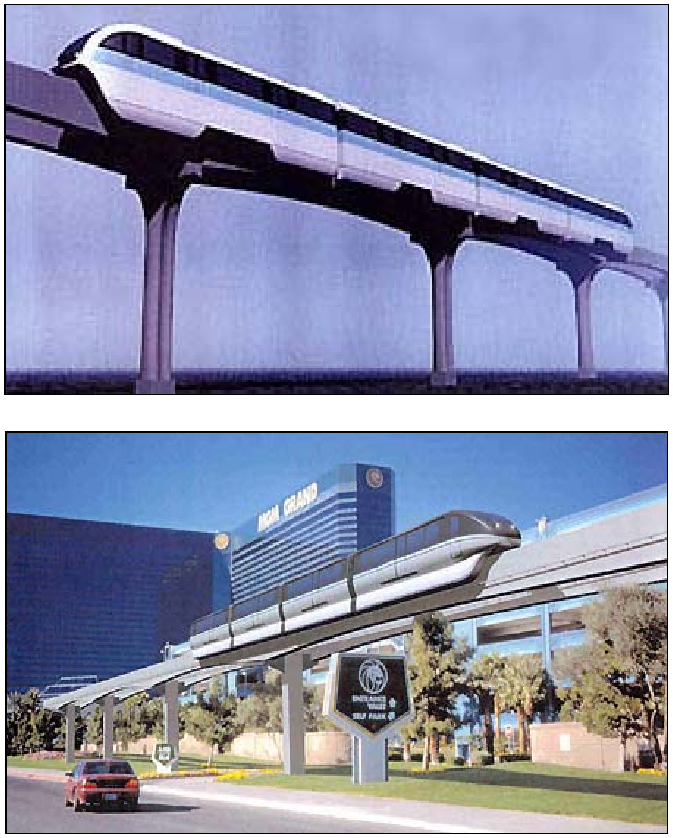

Figure 2.5—Two modern monorail aerial structures. Proposed Hitachi for Kuala Lumpur (Top) and Bombardier for Las Vegas (Bottom) The Bombardier aerial structure is the narrowest and most visually appealing of all the transit monorails mainly because trains are narrower than the competition and have a maximum gross axle load of only 8 metric tons.

"Straddle bents" are occasionally used in place of single columns, for example when crossing very wide streets, to allow vehicular passage underneath when a standard column would act as an obstruction. However, because of their size, they are avoided whenever possible.

Figure 2.6—Straddle Bent over Kuala Lumpur road. Source: Monorail Malaysia

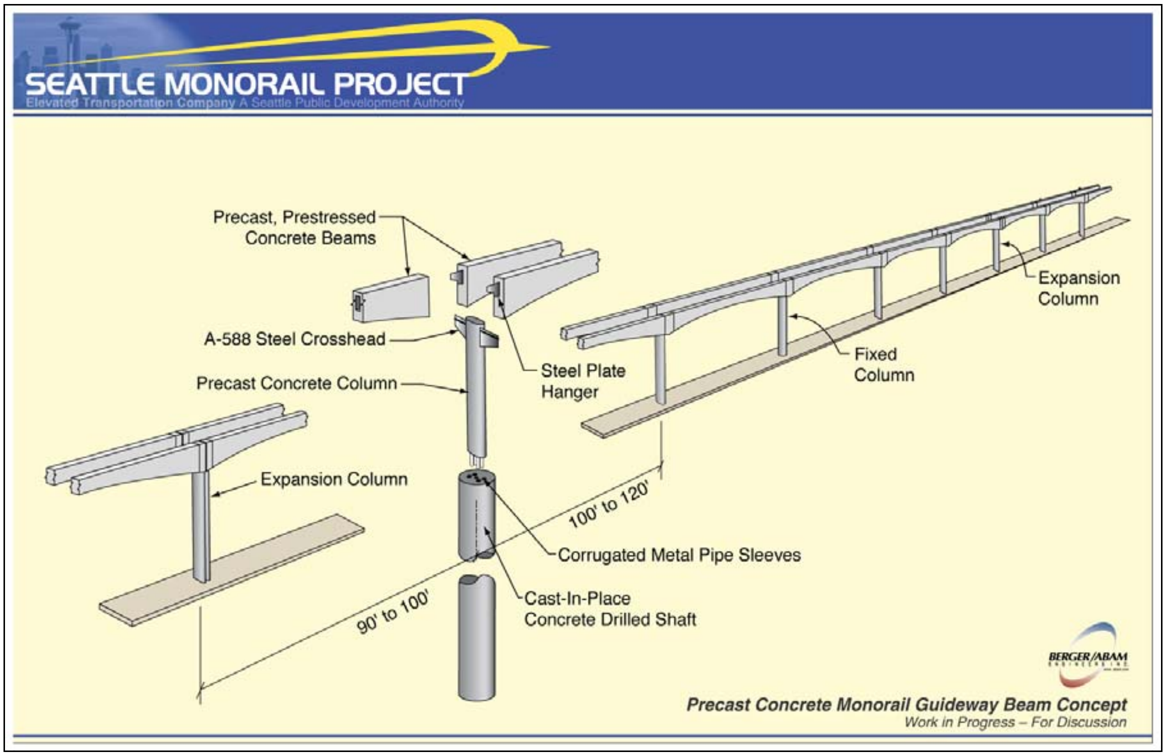

Figure 2.7— The new Seattle Monorail aerial structure may be the best yet. Source: Elevated Transportation Company.

Figure 2.8—Table of Aerial Structure dimensions.

Component	Alweg Seattle	Hitachi Large Type	Monorail Malaysia	Bombardier MVI	Hitachi Small Type
Guideway beam width	0.9 m	0.8 m/ 0.85m	0.8 m	0.66 m	0.70 m
Guideway beam height	1.5 m	1.4 m/ 1.5m	1.6 mid-2.2m end (arch)	1.5-2.1 m end (arch)	1.3 m
Std. span length	25 m	20 m/ 25m	30 m	30 m	?
Crosshead width	?	5.15 m	5.1 m	5.1m	4.5 m
Typical Column base	1.2 m x 1.2 m	?	1.2 m x 1.6 m	0.81 x 1.42	?
Max gross axle load	?	11 t/10 t	10 t	8 t	8 t
Minimum Curve Radius	?	70 M (40 depot)	70 m (40 m depot)	45 m	40 m

B. Straddle Monorail Vehicles

While all straddle-class monorail systems share a basic set of operating principles and are all built using advanced composite materials and have state-of-the-art variable voltage, variable frequency motors (VVVF), there is a wide range of design features among monorail vehicles.

As the first full-scale straddle monorail in operation, the Seattle Alweg train built for the 1962 World's Fair frames most of the major issues that still affect straddle monorail trains today.

Figure 2.9—The Seattle Alweg train interior. Source: The Monorail Society

- *Seattle Alweg*

One of the first things that one might notice about the Alweg train is that is built of articulated sections, not composed of coupled cars like its dual-rail competition. This was born out of a necessity to relieve pressure on the rubber tires and thus allow for tighter turning radii than would otherwise be possible.

This use of articulation was far ahead of its time. Such articulation was yet to be introduced to light rail and heavy rail trains. Fully articulated subway trains were only found in Japan until recently and are just now being introduced to transit-intensive European cities like Munich. While monorails trains are always articulated because the size of individual cars are not sufficient to handle the passenger capacity demanded of a capital-intensive rapid transit system, it should be noted that monorail trains can also be coupled together to create long trains for peak loads.

Although articulation was born from necessity, it had several unintended advantages. It allowed passengers to move freely between cars, which helped distribute passenger load throughout the length of the train and gave its passengers a feeling of security since they weren't in danger of being caught alone in a car with a criminal.

The Seattle train also provided amenities like very large windows to take advantage of the views to be had from 25 feet over the ground and to use natural lighting instead of electricity whenever possible. Also, the train operator was not given an individual compartment at the front of the train, but was placed with the passengers so that they could share the stunning view ahead.

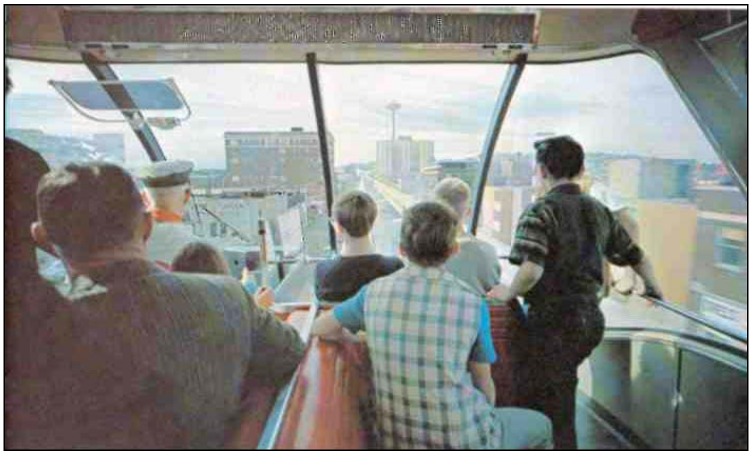

Figure 2.10—The Seattle Alweg offered its passengers a wonderful forward view. Source: The Alweg Archives

The design of monorail trains can also be related to the peculiar position and dimension of monorail supporting wheels. While the ability of straddle monorails to use a single slender guidance beam is one of the mode's major advantages, this also means that supporting wheels are located under the center of the cars rather than at the sides as in a dual-rail system. Reconciling this fact with the desire for maximizing passenger carrying capacities and efficiency of passenger circulation and minimizing unnecessary vehicle bulk among others involve certain tradeoffs.

The Alweg train addressed this concern by allowing the bogies to protrude into the passenger compartment, and placed seats over the wheels.   To avoid hindering circulation through the train, the train was very wide. It remains the widest of all the monorail trains, yet it does not come across as being ungainly so.

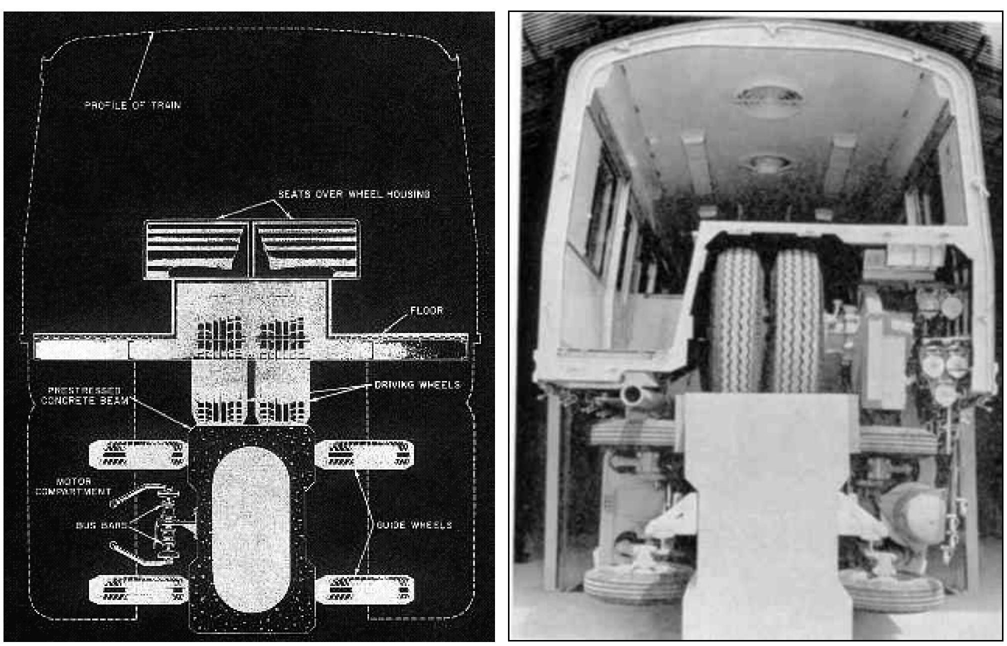

Figure 2.11—Cross-section of Alweg monorail showing seats over wheel housing, Source: The Alweg Archives

- *Hitachi*

Hitachi bought the rights from Alweg to develop a straddle-monorail system. The very first Hitachi vehicles followed the Alweg specifications closely. However, since then Hitachi has made several changes to their trains. Starting with the Tokyo Haneda monorail in 1964, Hitachi increased the length of monorail cars from about 10 meters to 14 meters. This was partly possible because Hitachi developed steerable bogies that allowed the longer vehicles to operate on the same turning radius, and partly possible because the Haneda monorail increased the number of load tires under each train to four from two.

The Series 1000 monorail was introduced with the Osaka system in 1980. The Series 1000 monorail unlike its predecessors did not have the support wheels protrude into the passenger compartment. Instead, the floor was raised about 1.1 meters above the beam so that the truck could be fully accommodated underneath. This allows for excellent circulation and more efficient seating plans, since a central aisle is now possible throughout the length of the train. While this development added to the height of the train, the incorporation of lightweight materials and a slightly shortened car allowed the gross axle load to remain constant.

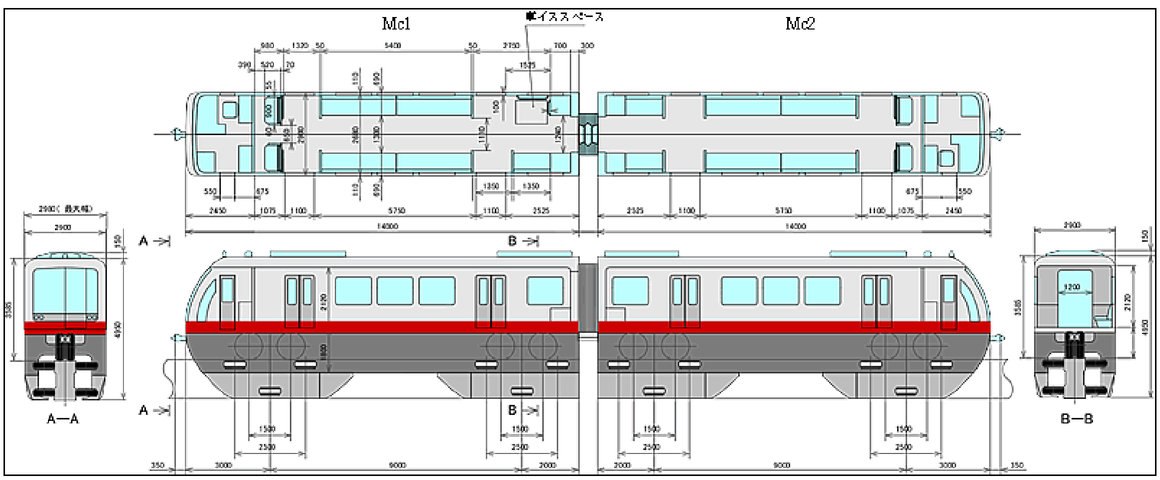

Figure 2.12—Hitachi Series 1000 Monorail for Naha, Okinawa. Hitachi Monorails can be coupled in trains up to 6 cars long. Source: Yui-Rail

While there is no necessity for seats in the center of the car under the new arrangement, and thus no need for wide cars to accommodate circulation around center seats, Hitachi has decided to keep approximately the same width for its newer models. This coupled with the cars' greater length as compared with the Seattle Alweg or Bombardier monorails, allow passenger capacities comparable to subway cars in Chicago, Montreal and Philadelphia, for example. And unlike those subways trains, the Hitachi monorails are fully articulated, meaning that passenger loads can be more evenly distributed among cars.

Figure 2.13—The automated Tokyo Disneyland monorail has deceptively cute Mickey Mouse windows, but this train is a workhorse: it has a normal capacity of some 600 passengers. Source: The Monorail Society

Many of the Series 1000 monorail's new features became the standard adopted by the Japanese ministry of transport in conjunction with the Japanese monorail association in a push to lower costs through standardization. However, updated trains that use the Haneda monorail specifications are still in production. In addition, Hitachi has been developing a much smaller, cheaper monorail train to compete with the Bombardier M-VI. Thus, Hitachi is the only major monorail manufacturer that offers several transit-grade monorails.

Figure 2.14—Small Hitachi train for Sentosa Island, Singapore. Source: Hitachi

While Hitachi monorails have been aesthetically lacking historically, more recent models such as the Okinawa and Tokyo Disneyland variations of the Series 1000 Monorail have done much to put a good face on what are very tall and bulky monorail trains. The internal aesthetics and comfort for passengers provide excellent compensation for its external clumsiness. Large, panoramic windows and attention to detail make for an enjoyable passenger experience.

Figure 2.15—Hitachi Monorail Interiors for Tokyo Disneyland (Left) & Naha, Okinawa (Right): Spacious, bright, large carrying capacities, fully-articulated and customizable. Sources: The Monorail Society/ Yui-Rail.

- *Bombardier MVI*

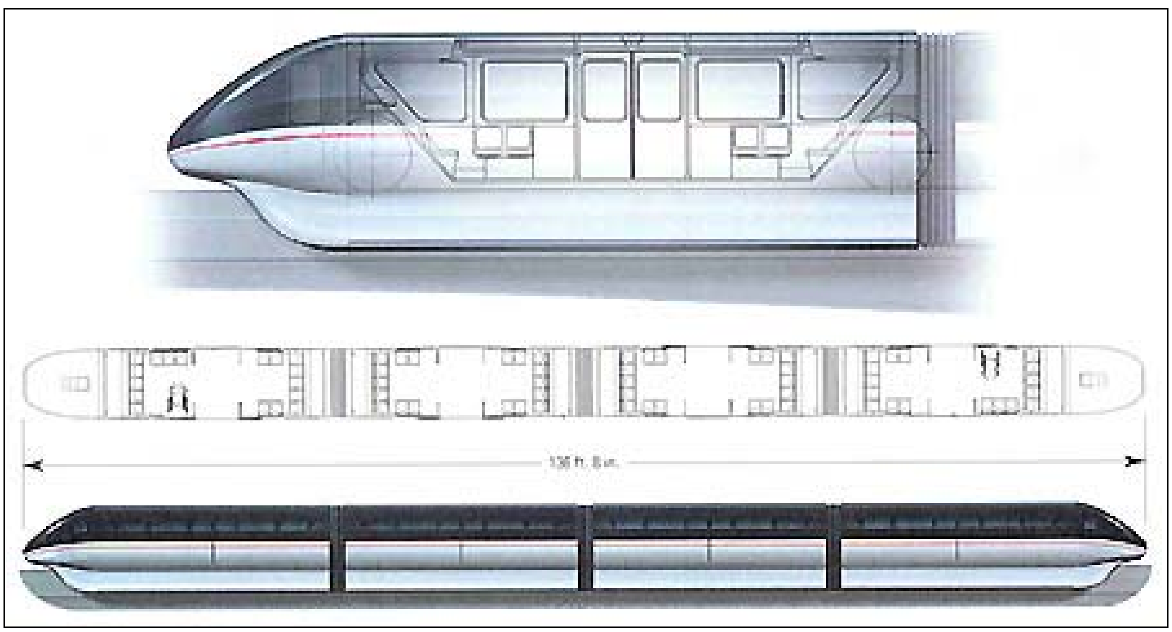

Figure 2.16—Bombardier Mark VI (Las Vegas Model), sleek and stunning but with no passenger-walk through between cars. Source: Las Vegas Monorail Company

Bombardier is generally recognized to have the most aesthetically pleasing monorail vehicle. This effect is primarily achieved by the decision to place supporting wheels between passenger compartments to achieve a low profile, lighter-weight vehicle that tightly hugs the guideway. While the height of the vehicle is less than the Alweg designs, the length of the cars is comparable even though carrying capacities are much reduced. Savings in vehicle costs seem negligible if cost/capacity is considered, especially when greater station platform length is factored in. The length of the vehicle devoted to housing the bogies is appreciable and seems wasteful. Nevertheless, Bombardier must be complemented for recognizing the not inconsequential role monorail's futuristic image and potential for aesthetically pleasing design could play in attracting riders.

Another example of this philosophy is the vehicle's prominent nose, which gives the vehicle a strong identity. However, the nose's physical separation from the passenger compartment and its low roof allows only enough room for a driver. This assignment of floor space seems even more suspect when automated train control is used in his place. This seems a poor design choice, in its Disneyworld ancestors, seating for passengers in the driver's compartment is provided allowing some passengers a wonderful front view.

That the bombardier vehicle is a descendent of the Disneyworld "Mark" monorails is apparent. Clearly, the designers of the vehicle made tradeoffs in support of aesthetic concerns. A sleeker vehicle and smaller guideway than its peers is the final result. Where moving very large numbers of people at the lowest cost is desired, this model is clearly not recommended. Passenger capacity is low compared to its peers due to its modest width and inaccessible space between cars. Even the modest capacity of 220 passengers per four-car train relies on a relatively high standee ratio. Where ridership is expected to be relatively small, where tourists are expected to contribute significantly to ridership, where passenger walk-through between cars is not necessary because of safety or other considerations, and where the right-of-way is narrow, the futuristic and fun image of this vehicle along with the low visual impact of the guideway structure may make this model this model very competitive.

- *Monorail Malaysia*

Figure 2.17—Monorail Malaysia two-car monorail train. Monorail Malaysia trains can be semi-permanently coupled into trains as long as twelve cars. Source: Monorail Malaysia

The newest monorail manufacturer's vehicle is a modern adaptation of the original Alweg in Seattle. Its dimensions are very close to that of the Alweg vehicle, and seats over the support wheels have been reintroduced having been phased out of the more modern Hitachi Series 1000 vehicles and missing entirely from the Bombardier/Walt Disney World models. Like the original Alweg model, there is no separate driver's compartment so that passengers have a view out of the forward window. While exterior design was not the top priority, it nevertheless looks attractive.

The train manages to achieve a balance between the higher carrying capacities of the Hitachi train and the pleasing aesthetics of the Bombardier model. For example, a Monorail Malaysia four car train is 10% shorter than a 4-car bombardier even though it has a 40 percent greater carrying capacity. Also, like the Hitachi models, full passenger walk-through is permitted. The Monorail Malaysia model also has a high ratio of door width to train length, resulting in faster loading and unloading than the other monorail models provide.

Figure 2.18—Monorail Malaysia train interior. The nearly ten foot width creates a sense of spaciousness despite the relatively low ceiling. Source: Elevated Transportation Company.

Figure 2.19—Table of Monorail Vehicle Characteristics

Characteristic	Hitachi Large Type [Series 1000]	Monorail Malaysia	Bombardier M-VI
Cars/Vehicle	2 minimum	2,4,6,8,10,12	3 minimum
Car Length	14 m	10.4 m end/8.6 m mid	11.8 m end/9.2 m mid
Width	2.98 m	3.0 m	2.64 m
Height	5.2 m	4.3 m	3.4 m
Walk Through?	Yes	Yes	No
Doors/side/car	2 sliding doors	2 “plug” doors	1 “plug” door
Door width	1.1 m	1.25 m	1.626 m
Bogie Placement	Under center aisle (under seats in series 2000 models)	Under center seats	At ends of cars
Axles per car	4	2	2
Max axle load	11/10 metric tons	10 metric tons	10 metric tons
Tare Weight of car	11 metric tons	~10 metric tons	
Suspension	Air	Air	Air
Power	1500 DC	750 or 1500 DC	750 DC
Motors per 4 car train	16 x 75kW AC (VVVF)	?	4x 110 kW AC
Max design/operating Speed	90/80 kph	90/80 kph	85/75 kph
Normal accel/decel. Rates	?	?	1.0m/s2
Normal Capacity Seated/Standing @4pers/sq.m (typical 4 car configuration)	415(177/238)	316(96/220)	224(84/140)

C. Straddle Monorail Implementation

The operation and operational principles of straddle monorail systems have had two major advances, one more philosophical, the adaptation of the straddle monorail to serve medium-capacity transit applications, and one more technical, the development and application of automation systems.

The former advance resulted from the upgrading of streetcar networks in Germany in the 1960s and 70s which developed into what is today known as light rail transit. Light rail offered a middle ground between the two modes that came to dominate public transit: high-capacity heavy rail systems and diesel bus networks. Light rail was cheaper and more flexible than heavy rail, while offering greater speed, comfort and reliability than buses. At this time, monorail's requirement of a fully exclusive right-of-way was seen as a liability. While the straddle monorail did not immediately benefit from the light-rail "revolution", the acceptance of medium-capacity systems has proven beneficial for monorail rapid transit in the long term because monorail was only a mediocre competitor for large heavy rail systems on the basis of performance, and was not at all competitive with buses in mixed-traffic because of the costs a fixed guideway entailed.

Light rail and the straddle monorail, two modes of transit developed with the intension of competing with the private auto as much as with other modes of public transit, were soon joined by a third option: automated guideway transit (AGT). Automated guideway transit tried to make a claim on the medium-capacity transit market not through ROW flexibility but rather by offering superior quality (i.e. greater frequency) service. Because vehicle operators were replaced by computers, smaller vehicles could be run more frequently, at all times of the day. However, like the early history of monorails, automated guideway transit found few major applications aside from people-moving shuttles, particularly at airports. Many of the initial demonstration projects were conducted by private and public groups more interested in the technical aspects of automation than motivated by the real needs of transit operators. The ability to operate with very small vehicles at extremely short headways was not valued outside of academic circles, for example. Often technologies like rubber-tires were used when they were not the most appropriate. Also, the guideway structures on which these "intelligent" vehicles ran were given little attention. Since AGT vehicles do not have a human driver to react to the near infinite number of situations can that occur when traveling in mixed traffic or in semi-exclusive right-of-way, AGT vehicles can only travel on fully controlled (i.e. exclusive) right-of-way. The expense of the guideway structure and the environmental impact of these structures were significant, and usually significant enough to make light rail the preferred medium-capacity mode.

Because the straddle monorail guideway is by far the least complex and most visually friendly, those that would traditionally have purchased traditional AGT systems are building automated straddle monorails instead. Many AGT systems operate with axle loads equal or greater than conventional modes, implying that guideway cost and complexity are more significant than most proponents propose. As explained in the beginning of Part Two, due to the distribution of vehicle weight, a straddle monorail guideway is lighter than conventional modes despite the vehicles' greater axle loading. In an attempt to make their elevated structures more palatable, AGT vehicles tend to be very narrow, averaging just a little over two meters in width. Monorail vehicles average nearly 3 meters in width. This width enables much more efficient interior design, passengers can be accommodated with greater comfort, and passenger circulation through the vehicle is much improved. Monorail's greater width also means that equal capacities could be accommodated with much smaller station lengths, an important consideration for transportation in tight urban spaces.

Just as automation has always needed a monorail-like system on which to be implemented, monorail can benefit greatly from automation. Whereas monorail's relatively costly, "inflexible" guideway made it appear inferior to light rail for the majority of medium capacity applications, light rail will not be able to benefit from automation due to its non-exclusive right-of-way.

What exactly are the benefits of automation? Automation allows transit operators to provide shorter headways between trains. Since drivers are not necessary, running two small trains every two minutes instead of one large train every four minutes is possible with equal, if not lesser resources. The benefits of automation are especially significant in providing high-quality service in off-peak times when transit economics do not usually allow frequent service. A reduction in headways from 15 to 5 minutes, for example, can encourage many more choice passengers to use public transit.

Orange County's multi-billion dollar light rail system will be slightly more expensive than a similar monorail since 85% of the route is to be elevated. Despite this investment, Orange County will see few benefits from having all this grade-separated right-of-way. Unlike the automated Seattle Monorail which will run trains every 4 or 8 minutes, the Orange county system will have 10 or 20 minute headways because operator wages are a significant limitation. Ridership will undoubtedly suffer as a consequence. The ability to eliminate vehicle operators, normally the single greatest transit operating cost, means that transit subsidies or ticket prices can be reduced and services such as security and maintenance can be supplemented. The ability of automated guideway transit to operate with reduced employees and thus reduced operating costs can be clearly seen in Figure 2.18. AGT systems such as the Vancouver Skytrain require no operating subsidies primarily because it can operate with just one employee per 150,000 annual passengers.

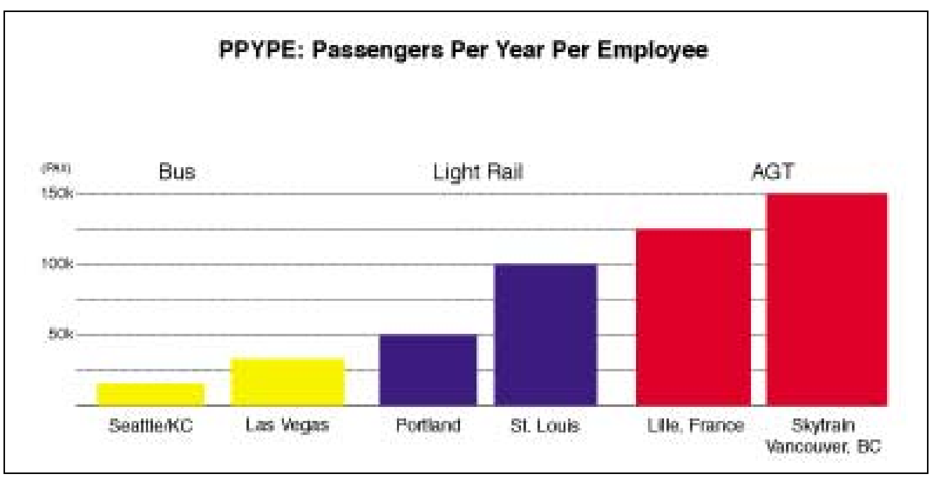

Figure 2.20—Automated guideway transit, which includes automated monorail systems, have greater passenger per employee ratios. Employees are the single greatest system operating cost element. Source: Dick Falkenbury

Automation also enables a slightly more efficient driving regime and greater passenger comfort for starts and stops. While this is not nearly as significant as operating at greater frequencies, it is nevertheless an advantage. Automated operating regimes have been shown to be extremely reliable and offer very high levels of safety.

While monorail transit has always had significant public support, drawbacks like slightly higher operating costs due to rubber-tired traction is partly to blame for transit operators' traditional skepticism of monorail technology. That automation addresses the operating costs in particular, thereby greatly improving system productivity, bodes well for future implementation of monorail rapid transit.

Conclusion

From an engineering point of view the basic characteristics of a straddle monorail's guideway and support has undergone little drastic change over a 40 year period. Computer aided design, and improvements in concrete constructions have helped somewhat. Much more significant is the appreciable amount of attention that has been paid to mapping out the tradeoffs involved with monorail aerials that will undoubtedly make this transit mode much more competitive.

Likewise, while monorail vehicles have benefited from modern transit technology, and are built to standards comparable to heavy and light rail vehicles, progress in design have been as impressive as improved technical standards.

Monorails have benefited from one major technological breakthrough: automation. While Asian monorails have increased automation tremendously since the monorails of the 1960's, they still have an operator on board. Full monorail automation will be introduced by the Las Vegas Monorail under construction.

PART THREE

Monorail as Cost-effective Urban Transportation

In the first part of this study, the basic components of monorail transit was shown to be sound, proven and practical for implementation in an urban setting. In the second part, it was concluded that straddle monorail technology has undergone significant refinement, and that this technology has been generally well applied to functional real world systems that have taken advantage of many of the most significant developments in transit engineering. Perhaps most importantly, several leaders in the transit manufacturing industry have shown interest(if not yet quite embraced) monorail technology and are now able to offer transit service providers a decent selection of monorail models to meet a range of needs.

At this point it must be considered fair to say that monorail rapid transit has been shown to currently meet the first test for assessing transit systems: it is “technologically and operationally sound.” However, for monorail to be a valid form of urban transit, it must meet a second requirement as well, as stated by Vukan R. Vuchic: “that it provides a cost/benefit package that is at least equal to more traditional transit technologies.” Thus, the cost of monorail construction must be considered, especially in reference to the cost of alternatives. Since monorail is a fixed line system, a comparison with traditional rail systems makes sense. Since monorail shares the characteristic of having exclusive right of way with heavy rail, a comparison with that mode should be made. Also, because monorail shares the ability to carry moderate numbers of people along public thoroughfares with light rail, a comparison to light rail is also appropriate. Bus rapid transit (BRT) would also be an appropriate comparison, but since very few true BRTs are in operation in North America at this time and because there are a wide range of costs and nearly infinite range exclusivities/alignments, this mode will not be compared.

A. Monorail Capital Costs

- Expected costs

Monorail is usually elevated, its guideway supported by aerial columns, but it can also run at or near surface level, or underground in a tunnel. Capital funds for a monorail system are mainly spent on the aerial structure—the columns and guideways—and on the stations and monorail vehicles. The Tama monorail in Japan has tunneled portions, but since tunneling is several times more expensive than elevating the guideway, such alignments are avoided as much as possible. Because of the height of monorail vehicles, tunneling costs for bored tunnels are somewhat greater than heavy rail with third rail. Because of the small footprint of monorail systems and their extensive use of public rights-of-way, "softer" costs not associated with actual construction are a generally smaller percentage of total capital costs than similar traditional rail technologies. These soft costs can be considerable, particularly in North America where legal issues and rigorous environmental review impose especially high costs.

- Actual Costs

Costs for the construction of transit systems are notoriously hard to pin down. Sometimes quoted costs include only the cost of the construction while for others design and or mitigation vehicle costs are included. Generalizing costs are even more difficult when costs vary widely from system to system, location to location. To provide for the fairest comparison, all projects have been recently planned or constructed systems are selected to exemplify a range of characteristics (lengths, configurations, alignments, etc.) By focusing on recently built and currently planned lines, dollar amounts are not affected by general inflation nor are they affected by increasing or decreasing costs relative to inflation on elements like concrete, steel or wages in the construction industry.

Figure 3.1—Monorail System Costs

System	Length	Cost	Cost/mile	Comments
Naha, Okinawa (Hitachi)	7.8 miles	$533 million (70.4 billion yen)	$68 million	Includes two-car Trains, driver operated
Kuala Lumpur Monorail (Monorail Malaysia)	5.3 miles	$311 million (1.18 billion ringit)	$59 million	Includes two-car Trains. 11 Stations
Las Vegas Monorail (Bombardier)	3.6 miles	$352 million	$98 million	Automated. Includes nine 4 car trains. Elaborate Stations built for 8 car trains(initially operated with 4 car trains).
Las Vegas Downtown extension(Bombardier)	3.1 miles	$337 million	$109 million	See above.

Seattle Green Line	14 miles	$1.25 billion	$87 million	Costs include bridging of two major bodies of water. Fully Automated. Four car trains to be used.

- Comments

Monorail capital cost in current-year dollars (including both "hard" and "soft" capital costs) amount to $60 to $80 million per mile for systems with capacities comparable to most light rail operation in North America where 2 car trains are typically used with 5-6 minute headways. A combination of larger monorail trains, with a capacity comparable to smaller rapid transit systems, system automation and difficult alignments can raise the cost of the system to over $100 million and perhaps as much as approximately $130 million in the most extreme cases. Despite the common claim that monorail costs are unpredictable, the evidence shows monorail costs to be reasonably consistent and differences in cost are easily related to train and station length i.e. capacity, and automation.

CASE STUDY—Components of a monorail system

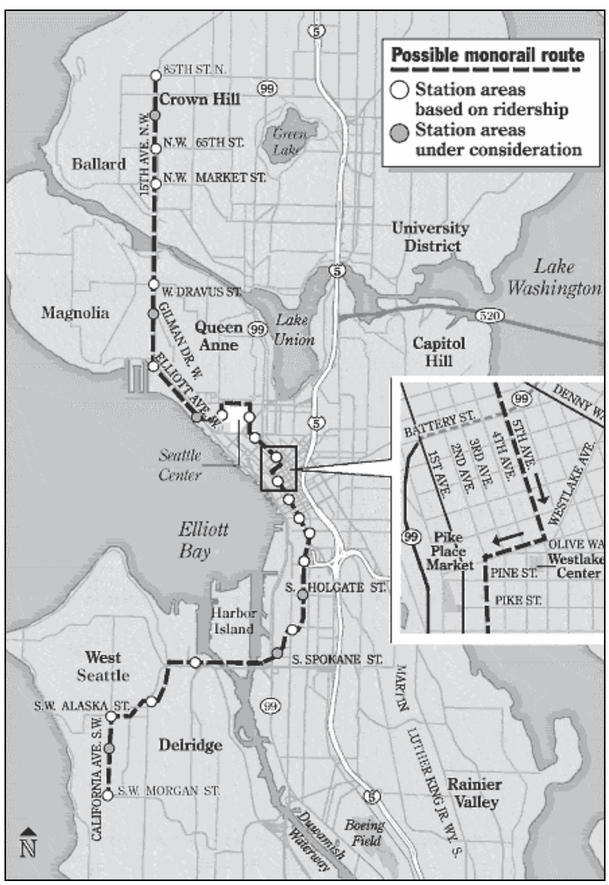

Figure 3.2—the 14 mile long Seattle Green Line. Source: The Seattle Times

Seattle Green Line:

- 14 miles of dual aerial guideway with 19 stations.
- $ 1.29 billion including contingencies
- Cost includes a new monorail-only bridge and the strengthening of a second bridge to accommodate monorail system.
- Trains included in cost estimate can accommodate minimum of 3000 pphpd at 4 minute intervals.
- Expected to carry 69,000 passengers daily in 2020.

Figure 3.3—Table of Seattle Green Line Monorail costs compared with other rail systems relative costs

System Component	Green Line Costs	Percent of Total	Light Rail averages (range)	Heavy Rail averages (range)
Trains and Control Systems	$255 million	20.3 %	13.0 %(vehicles only)	20.8 %
Power	$95 million	7.6 %	10.1 % (power and systems)	3.2%
Stations	$110 million	8.8 %	5.2 %	26.0 %
Maintenance Facilities	$30 million	2.4 %	4.9 %	2.2 %
Beams, Columns and Foundations (= guideway and track for dual rail)	$290 million	23.1 %	23.2 %	29.4 %
Water Crossings	$120 million	9.6 %	-	-
Right of way acquisition	$30 million	2.4 %	8.2 %	5.8 %
Utility relocation	$80 million	6.4 %	See below	-
Design and Administration	$235 million	18.7 %	29.2 %(soft costs)	15.0 %

Source: Elevated Transportation Company/

- Monorail vehicle and system costs make up a greater proportion of total costs than do light rail or heavy rail. This is mainly due to the expense of system automation, which reduces operating costs and having many small vehicles rather than fewer, larger vehicles so that time between trains is reduced.

- Monorail station costs are much less than heavy rail and only slightly more than light rail even though light rail stations tend to be at grade and have significantly less amenities. Here we can also see the benefit of employing smaller, more frequent trains which reduce station size. Heavy rail stations often have the increased burden of having to be dug into bedrock at great expense.

- Monorail guideway cost as a proportion of total costs is equal to that of light rail. This is a surprising finding since light rail track work is normally thought to a cheaper system element than monorail's concrete beams, columns and crossbars. This difference in perception is probably due to costs like street-reconstruction necessary before the track can be laid. Another factor is the frequent use of light rail aerials more costly than the standard monorail aerial. The greater percentage of guideway costs for heavy rail systems can be explained by this mode's frequent use of expensive tunneling.

- Monorail maintenance facilities are a small cost element. Monorail trains and guideway need relatively little maintenance.

- The percentage of total costs spent on acquiring right-of-way is very low for monorail system, due to monorail's ability to almost exclusively use airspace over the public right-of-way. This is a significant cost-element in light rail systems. Unlike spending on control systems, there is little return on this investment.

- The bridging of waterways is a major cost element of the Seattle system. Most monorail (or light and heavy rail) systems would not be faced with such extraordinary costs.

- Utility relocation is included with the cost of the Seattle system, although these costs are frequently the responsibility of utility companies.

- In the Seattle system, design and administrative costs have been kept relatively low, supporting the claim of lower "soft"-costs. While heavy rail systems manage to spend a lower share of total funds on such costs, this probably reflects very high "hard" costs rather than any savings in soft costs.

B. Comparing Conventional Rail Systems to Monorail

Cost is undoubtedly a major determinant of choosing particular transit technology. By supplementing information on monorail costs and potential benefits with the costs and details of non-monorail rail alternatives, we can ascertain the conditions, if any, under which straddle monorails would be able to compete with dual-rail systems.

Figure 3.4—Various Light and Heavy Rail System Costs in North America

(Please note: Costs taken from FTA web site wherever possible and are in YOE dollars)

Rail System	Length	Total Cost	Cost/mile	Comments
Portland Streetcar	2.4 miles	$ 57 million	$23.8 million	ROW C, operates in mixed traffic
Portland Interstate LRT	5.8 miles	$350 million	$60 million	ROW B, addition to large LRT system
Phoenix/Tempe	20.3 miles	$1.06 billion	$54.4 million	ROW B
Houston	7.5 miles	$300 million	$40 million	ROW B
NYC-NJ Hudson-Bergen LRT	20.1 miles	$2.0 billion	$100 million	ROW B, in dense urban area.
San Francisco 3rd St. LRT Phase One	5.4 miles	$530 million	$98 million	ROW B, in dense urban area.
Salt Lake City CBD to Univ LRT	2.5 miles	$118 million	$47 million	ROW B
Salt Lake City N-S LRT	15 miles	$312 million	$21 million	ROW A, at grade. Cost does not include ROW acquisition.
Metrolink St. Clair(St.Louis) Extension	17.4 miles	$339 million	$19.5 million	Suburban extension following fmr railroad
Denver	19 miles	$879 million	$46 million	
Eastside Corridor L.A.	5.9 miles	$759 million	$129 million	Primarily ROW B, with 1.8 mile tunnel.
San Fran,. 3rd st. LRT Phase 2	1.7 miles	$876 million	$515 million	ROW A, Phase Two is built as a tunnel through downtown.
Seattle Central Link LRT-Phase One	13.9 miles	$2.23 billion	$ 160 million	Primarily ROW B, with portions tunneled and elevated
Orange county-Centerline Rail Corridor	30.1 miles	$3.74 billion	$124 million	90% ROW A elevated and 10% ROW B in street.
Atlanta North Line Extension	2.3 miles	$463 million	$201 million	Suburban heavy rail extension

SFO BART extension	8.7 miles	$1.51 billion	$174 million	Heavy Rail. Suburban extension to airport. At grade, in tunnel and elevated segments.
Largo Metrorail Extension	3.1 mile	$433 million	$140 million	Suburban Heavy Rail extension.
L.A. Red Line Subway	17.4 miles	$5.6 billion	$322 million	Heavy Rail, nearly all of it tunneled.

- Comments

Traditional rail systems, even among a particular category like "light rail transit", show much more variation, as compared with monorail systems. The range is huge: From a low of $23.8 million/mile for the Portland Streetcar to a high of $515 million/mile for Phase Two of the 3rd Street corridor in San Francisco. I propose the widely varying costs of rail can be explained primarily by two characteristics of their alignments: the exclusivity of their right-of-way, from non-exclusive right-of-way (ROW C) to fully-exclusive right-of-way (ROW A) and particularly the costs involved with buying or creating exclusive right-of-way. By taking this approach we can compare monorail generally to categories of traditional rail without having to compare the two on a detailed case-by-case basis, although we will review the Seattle Intermediate Transit study, a rare study that compares the two technologies on a particular urban corridor.

- **ROW C**

Traditional rail transit that travels in mixed traffic like the Portland streetcar is much cheaper than monorail. The Portland Streetcar costs roughly 1/3 to 1/4 of a full-sized monorail system. ROW C, however, offers such low quality of service (marginally better than buses in mixed traffic) that a comparison between it and transit-grade monorail is probably pointless. One hopes that when such a system is contemplated, its use will be to encourage tourism and real estate investment and for very local transport. While monorail can be a tourist draw and encourage investment, it is by its nature a poor means to transport passengers over short distances in urban environments. Numerous elevated circulator systems in US downtowns like Miami and Detroit have tended to be unsuccessful because of the real or perceived burden of entering a station for a short journey, and a circular alignment means it is often faster to walk directly to your destination.

- **ROW B**

ROW B rail transit will generally be one-half to two-thirds of the cost of a transit grade monorail system. This represents a significant difference. However, I would posit that monorail is worth considering as an alternative. Monorail, despite higher costs, would likely see increased ridership due to the speed and frequency advantage monorail (ROW A) would likely have over ROW B travel. Additionally, when externalities caused by running rail at grade, such as reduction in vehicle lanes or indirect costs imposed on surrounding businesses due to construction are considered, monorail may very well prove to be the less expensive choice.

There is evidence that suggests ROW B projects in very dense urban environments like San Francisco (Third St. Project) and New York-New Jersey (Hudson Bergen) can cost as much as a similar monorail system due to costs like street reconstruction, environmental mitigation and hazardous materials removal. Straddle monorails have a small footprint, and much construction can be done off-site, meaning that monorail would have relatively few additional costs in these urban alignments.

Figure 3.5—The spectacular view from a monorail can attract riders that might not have used rail transit at grade or in a tunnel. Speed is another factor in monorail's ability to attract riders. Source: Monorail Malaysia

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CASE STUDY—Monorail or semi-exclusive light rail?

The *Seattle Intermediate Capacity Study* looked at a "streetcar" (light rail transit at ROW B) and compared it to "elevated" (Monorail) and Bus rapid Transit (Bus semi-rapid transit) along a major north-south 15-25 mile long corridor through downtown Seattle. The streetcar alternatives were somewhat cheaper to build, but for the northern half of the corridor, elevated monorail was strongly recommended by the study and monorail was a strong contender even in the less densely populated southern corridor due to higher ridership, lower operating costs and significant benefits to riders. A summary of findings for the corridor:

- Capital costs

Monorail alternatives range between $1.18 and $1.93 billion and streetcar from $1.05 to $1.08 billion (note: the monorail alternatives include some longer line lengths than the streetcar alternatives.)

- Ridership

Expected ridership on the monorail was in a range of 19 to 25 million passengers per year, while LRT had only 12 to 14 million passengers per year.

- Operating costs

An automated monorail system would have considerably lower annual operating costs with a range of $11 to $22 million, while LRT costs had a range of $33 to $38 million.

- Total Costs

Cost per boarding (Operating plus Annualized Capital Costs): $5.70-$7.05 per monorail boarding vs. $9-$10.90 per LRT boarding. The incremental cost per incremental (new) rider for the alternatives revealed a similar ratio.

- Time Savings

Time savings is an example of a system's value to society. The annual value of travel time savings for existing bus riders was in a range of $33 to $55 million per year with monorail, but only at $3.6 to $10.4 million with the LRT alternatives.

Source: Parson Brinckerhoff, Quade and Douglas

- **ROW B with ROW A at grade**(for the sake of simplicity "ROW A at grade" also includes alignments where there is the occasional at grade street-crossing of the tracks, as long as the tracks are not on-street.)

A mixture of ROW B with ROW A at grade is a common layout for LRT lines particularly in the Mid-West, South and Mountain-West. While in the dense but small downtowns of cities such as St. Louis, Dallas and Edmonton these lines travel along streets, but beginning immediately outside of these downtowns the intensity of land-use is rather low, resulting in inexpensive right of way costs. This right of way is sometimes in the form of freeway medians or abandoned railway corridors, or even mixing with operating longer-distance rail lines in the case Karlsruhe, Germany.

Interestingly, the costs for such systems are often significantly less than alignments which run exclusively in ROW B because street reconstruction and associated costs are often significant, and empty land in these cities is often cheap. A typical trap with this type of system is to rely on cheap rights of way that do not serve your riding population. This potential trap can, however, be overcome by employing Park and Rides and more recently, through the encouragement of TODs (Transit Oriented Developments) which allow riders to be brought to transit rather than vice-versa; although there are additional costs associated with Park and Rides and waiting for TODs to be built, of course. Given the bulk of the monorail guideway and its inability to be crossed by other traffic when at grade, only nominal reductions in cost can be achieved by running at grade as opposed to twenty feet above a road. This means that even with no right of way acquisition costs, a monorail would most likely not be able to compete with light rail running in such an alignment.

- **ROW A in tunnels or elevated(with or without ROW B service)**

Recently, a number of light Rail systems have been proposed with large portions of the alignment underground. Light Rail systems that use tunneling is, in itself, nothing new; the various arms of the excellent 1900 Boston Green line converge in a tunnel downtown, thereby avoiding narrow, congested streets. The tunnel portion of the line is well-used because more frequent service by numerous branches can be offered, multiple berths are provided so that 120 seconds or fewer intervals between trains are possible, and are indeed common. Also numerous light rail systems in Europe use tunnels in central areas where numerous light rail lines converge; multiple lines can thus "share" the cost.

More recent light rail systems have proposed using significantly more tunneling, often in areas where density is not particularly high. The 23.5 mile Seattle Central Link light rail line, the initial segment of which is nearing construction, will use about 8 miles of very expensive bored tunnel, another 5 miles of at grade or elevated ROW A, and the rest as ROW B in a the median of a avenue that will be widened for the purpose. In this case, relatively few miles of ROW B can be seen as a reduction in service quality (slower max. speed at roughly 35mph and cross traffic considerations act as limitations to capacity) of a line largely built to very expensive rapid transit specifications.

While grade and alignment issues in the Seattle example ask whether monorail could follow the light rail alignment exactly, monorail would be extremely competitive cost-wise. With monorail, constant ROW A could be had at a much lower price, with all the accompanying benefits like higher frequency of service, and reduced operating costs. The 5.9 mile LRT Eastside corridor in Los Angles will cost $129 million/mile (near the upper end of monorail systems) because of a 1.8 mile tunnel in the middle of its alignment. This suggests that if as little as, perhaps, 20 to 25 percent of a LRT alignment is tunneled, monorail without tunneled segments would have the clear advantage in capital costs (not to mention cost/benefit ratios.)

The cost savings by building monorail instead of elevated light rail is appreciably less than building monorail instead of tunneled light rail. According to the Elevated Transportation Company's *Technology Alternatives Narrowing Paper*, AGT and ALR systems have approximately the same vehicle and system costs as monorail, but the guideway cost is about 15 to 30 percent greater due to the wider concrete deck and the additional required guidance hardware"(i.e. tracks). This margin is small but not insignificant

Furthermore, since the impact of elevated light rail is much greater than monorail, elevated light rail may have to be placed in a no-man's land next to a freeway when monorail could be placed right down Main Street, meaning more benefit. Even if elevated light rail could theoretically be placed down "Main Street," negative environmental externalities would be much greater than with monorail. (Figure 3.6).

Figure 3.6—Monorail has the lowest impact of any elevated rail system. Notice the difference in shadowing effects between monorail and light rail aerials (Kuala Lumpur guideway (right), Projected Seattle light rail aerial (left). Source: Monorail Malaysia/ Sound Transit.

There are clear signs that numerous cities need rapid transit quality service, but do not have the funds (or believe they can not get them) necessary for heavy rail. The claim that buses are more "flexible" than rail is one of the most common claims made against rail transit. While this is true, this claim is far too often used by apologists to justify a reduction in transit spending, rather than being based on sound analysis of transit needs. Ironically, some complex light rail projects are justified by the mode's "flexibility" by pro-transit supporters who recognize that politicians don't want to be seen as throwing public funds at large, "old-fashioned" and "unwieldy" projects like heavy rail. The result is a light rail line that costs nearly as much as heavy rail, but with much lower quality of service. It does not make sense that LRT, an approach that first worked wonders in small and medium sized German cities should function as the transit backbones of very large cities like Seattle and Los Angeles. Monorail offers an attractive alternative to such over-extended, but under-performing light rail projects.

- **ROW A—Heavy Rail**

Monorail may be competitive with smaller heavy rail transit systems. Hitachi Monorails like the Tokyo-Haneda Monorail can carry capacities of up to about 30,000 pphpd. While monorails could theoretically be ten or even twelve cars long, such trains would require large stations that could undermine monorail's claim to having low impact on the urban environment. Although, due to monorail's cost advantage over dual rail systems in tunnels, it may be the case that two monorail 4-6 car monorail lines could serve the same population with the same quality of service, much more effectively than a single busy subway line, at the same price. However, it must be noted that rubber-tired straddle monorails cannot, with present technology, match the speeds of certain rapid transit systems which travel long distances like BART in the Bay area or the Washington Metro, both of which have maximum speeds in excess of 70 mph. For reasons of speed and cost, straddle monorails also cannot currently compete with commuter or regional rail which mainly use at-grade alignments and travel with maximum speeds exceeding 60mph and even approaching 100mph on select electrified lines.

Figure 3.7—Conditions favoring monorail rapid transit.

Characteristic	Recommended Value/Features	Justification
Line Length	4 to 30 miles	At lower values, time savings from ROW A travel becomes appreciable and elevated stations become practical despite cost. At upper values, monorail can not compete with the faster speed of heavy rail, and cheap land for at-grade ROW A becomes increasingly common.
Station Spacing	1/3 to 2 miles	
Maximum line direction capacity with normal loads (4 standees/sq meter)	5,000 to 20,000pphpd	At lower value, monorail investment costs become justified. At upper value, monorail train & station bulk become system liabilities and advantages from automation (operating cost, quality of service) become negligible.
Population/Employment Density	Low-Medium to Medium-High	Elevated transportation can be problematic in areas with single-family home densities due to privacy concerns. Extremely high densities may make accommodating space needed for monorail and monorail stations challenging.
City Age/ Image	Modern	Monorails' aesthetics are less questionable in modern cities, or in areas with modern architecture.
Geological/Environmental conditions	The more difficult and problematic, generally the greater Monorail's advantage over conventional rail.	Monorail can be a cost-effective alternative to tunneling; aerials act as mini- bridges over sensitive spots and monorail structures have a small footprint.

Figure 3.8—Monorails help complete a futuristic image in a modern city or in areas with modern architecture. Monorail has a reasonably low environmental impact; this row of stately trees in Kuala Lumpur would likely have had been removed if any other rail system was built. Source: Monorail Malaysia

Conclusion

If fixed-rail transit systems are built to their cost/benefit potentials, they would include ROW C light rail, ROW B dominant light rail, ROW B with ROW A at grade light rail, monorails and heavy rail. Interestingly, these modes correspond quite well to the age of transit in the pre-automobile era in North America. On-street light rail is essentially the modern, upgraded (in ROW B) equivalent of the Streetcar. Light rail running in ROW A outside of urban centers harkens back to the numerous interurbans which linked up neighboring cities, suburbs and towns. Monorail is essentially a much-improved reincarnation of the "L's" that used to cross Manhattan and Boston and which still serve Chicago. Today's heavy rail systems are subways for the very "tallest" of cities, and regional rail is the improved form of yesteryear's commuter railways for the "widest" of metropolitan areas that sprawl over large distances.

Manhattan demolished its elevated railways in favor of subways because one, the elevateds were running at capacity and two, because their bulky structures and noisy, polluting (coal powered) operation were a burden on their surroundings. Unlike Manhattan, few cities in the United States or Canada have the riderbase needed to justify subways. Furthermore, a straddle-monorail's environmental impact is extremely small in comparison to its bothersome predecessors.

It is recommended that transit monorails be built to a size and capacity that would be at least that of the larger ROW B light rail systems, but no larger than the smaller subway systems, i.e. approximately 6 X 15m cars long. If monorail aerials can be accepted into the streetscape of North America's metropolises, and there is growing evidence that they can, then monorail rapid transit could become an important mode of transportation in North American cities.

Figure 3.9—If downtown Chicago has prospered in the shadow of its bulky and noisy elevated system, imagine what cities with a street-friendly monorail system would do for other downtowns. Chicago "L" (top), Planned downtown Seattle monorail station integrated with a new development (below). Sources: John Bell/ Elevated Transportation Company.

GENERAL CONCLUSION

There is a clear need for high-performing, moderate cost, medium to medium high capacity transit in North America. While monorails have seen most interest in Asia, monorail rapid transit is perhaps even more suitable to North American cities with their more modest densities and riderbases.

The most likely candidates for monorail within North America include numerous large Western metropolises with little or no previous railway structure to upgrade. The cost of acquiring right-of-way and of building new traditional dual-rail infrastructure is often prohibitive in these built up and often geographically and geologically restrained metropolises. Seattle, Los Angeles, Honolulu and Las Vegas are cities with unmet transit needs, little or no pre-existing transit infrastructure and high land values. It is precisely these cities which have at one time or another contemplated monorail rapid transit. As stated in the introduction Las Vegas is now constructing a transit-grade monorail system and Seattle will likely begin one in the near future. But it is along major corridors in the megalopolis of Los Angeles which would most benefit from monorail infrastructure since density is rarely high enough for heavy rail yet distances are too great for semi-exclusive light rail or bus semi-rapid transit to make sizable contributions.

In the eastern half of the continent, monorail systems could serve as feeders or links to established traditional rail systems, particularly in and between so-called “Edge cities”: rapidly urbanizing suburban areas. Metro Atlanta has many such areas with severe congestion but with little chance of being served by Marta, the heavy rail system. The same is true for the area around the Washington DC Beltway where Metro service is unlikely because of cost considerations. Monorail rapid transit might also be ideal for Boston’s urban ring corridor, and other built-up urban areas bypassed by the glory years of subway construction at the beginning of the twentieth century. Monorail also lends itself to numerous “undiscovered” corridors where fixed transit has not been contemplated due to the limitations of traditional rail technology. An example of this would be a monorail line along portions of the Manhattan waterfront, perhaps linking downtown with the convention center midtown. While any other elevated system would be unacceptable, the low environmental impact of monorail and the ability to integrate the line into buildings make such a project conceivable.

There should be no doubt that monorail rapid transit would serve a niche, it would be not a transportation cure-all. However, this niche is certainly an important one that includes some of the most difficult urban alignments in some of the most mobility-impaired cities on the continent. This study has found substantial progress in monorail trains and guideways and found monorail to be a near ideal fit for advanced automation made possible by advancements in computing. Investment in automation will likely see its greatest return in North America where wages and associated costs tend to be higher than in most Asian cities and where monorail systems will likely be smaller; in other words, where productivity per operator would be lower. The real test for the acceptance and suitability of monorail rapid transit in North America will be Seattle’s 14 mile Green line, where many of the best and most appropriate aspects of monorail technology such as visually pleasing aerials and full automation have been incorporated.

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