Abstract

New technologies offer ways for railroads to reduce costs, increase market share, and achieve higher profitability. Determining the best opportunities requires understanding of the marketplace and translation of technological improvements into competitive advantage for the rail industry. This three-year research effort uses the Performance-Based Technology Scanning (PBTS) methodology for identifying such ‘leveraged’ areas. Applying PBTS to intercity passenger rail revealed that line-haul speeds and access times are both very important. High line-haul speeds differentiate the service from the private auto, while better access time competes with air service.

The current high-speed rail research programmes in the United States have focused on two distinct approaches: (a) upgrading existing rights-of-way through conventional technologies such as tilting vehicles, track realignment and positive train control to enable service speeds of up to 150mph; (b) constructing new rights-of-way with advanced propulsion technologies such as magnetic levitation to enable service speeds of up to 300mph. The former approach sometimes fail to make appreciable difference in journey time or market share, and introduces conflicts with freight trains, while the latter isn’t currently considered economical for corridors longer than about 30 miles, due to the high cost of new infrastructure.

We therefore recommend a hybrid approach for further engineering research & development. Rail vehicles with magnetic guidance equipment could travel as conventional trains over “wide open spaces” on low-cost existing rights-of-way at up to 110mph, then switch to magnetic guidance to climb very steep grades or achieve higher speeds around sharp curves. Climbing steep grades allows more direct new routes through mountains, avoiding potentially costly tunnels. Maintaining stability with magnetic guidance allows usage of existing, curvaceous infrastructure at higher speeds to reach downtown areas. Hybrid maglev vehicles and railroad maglevication is backwards compatible, thus allows sharing of the high, fixed infrastructure costs with commuter and freight trains already running over the national rail network.

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Introduction

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In this paper, we introduce the concept of maglevication of existing railroad infrastructure. When Pennsylvania Railroad electrified the Philadelphia-Paoli mainline in 1914, they designed the catenary such that ordinary steam freight trains could run ‘under the wires’ to reach Lancaster and points beyond. Maglev could be seen as the next step forward – and maglev infrastructure should be designed such that ordinary diesel freight trains could run ‘over the magnet’. More importantly, since maglev infrastructure is expensive, express passenger trains should be able to switch between maglev and conventional modes, to navigate different types of terrain at different speeds. We call this process of retro-fitting magnetic infrastructure to existing railroads the process of railroad maglevication.

Lifting the steel wheels from the track may not actually be necessary to achieve the range of journey time savings customers desire. With advanced truck designs, rolling contact resistance could be substantially decreased compared to the typical levels when maglev trains were first proposed. Maglevication would utilize the existing steel wheel-rail interface to provide support for the weight of the rolling stock, while utilizing magnetic forces to assist horizontal and lateral movements.

Performance Based Technology Scanning

PBTS is a methodology whereby the process of determining the technology strategy for railroad carriers and industry is broken down into five distinctive steps, ranging from the general broad-brush explorations to the very specific strategic direction. The highest level is a generalized search for new and emerging technologies, often conducted by science and engineering graduates using industry sources and the science...
The objective is to identify novel and exciting technologies that may have an impact on the transportation industry. Technologies can affect transportation in quite subtle ways: travel patterns, nature of goods being transported, the technologies available to transport them, and the relative economics of different modes, could all change with new technological development.

Two approaches of classifying the impact of technologies could be distinguished: (a) Technology Mapping, and (b) Customer Requirements Analysis. The former is a “technology push” approach where vendors of technologies identified in Step 1 attempt to identify the areas where the emerging technologies could be applied to transportation. The latter is a “market-pull” approach where transportation companies actively seek technological solutions to existing operational problems. The potential technological applications are then evaluated using a comparative technology evaluation framework to ascertain whether the proposal will generate the best net social benefit (versus not deploying the technology, or deploying an alternate technology), in Step 3. The final step is to develop and implement the most promising (or leveraged) ideas. Substantial development costs could be incurred at this stage, and the comparative technology evaluation serves as a screening process to differentiate between lemons and silver bullets.

Detailed discussion of the PBTS process developed as part of this project is detailed in a prior publication (Lu, Martland, et al., WP-2002-3). In the present paper, a promising idea for high-speed ground transportation, as identified in the Step 3 of the PBTS process is described.

The State of Practice in High Speed Ground Transportation

There are a number of technologies currently competing for the 100~600 mile transportation market in the developed world. Amongst them: (1) private auto, (2) intercity buses, (3) conventional train, (4) high-speed train, (5) magnetically levitated train, (6) conventional aircraft, (7) tiltrotor and other light aircrafts. There are also a number of permutations of each type of technology, e.g. high-speed trains could be electrically propelled, gas-turbine driven, or carry diesel prime movers; conventional aircrafts could be large aircrafts or regional jets. The argument between whether airbourne or land-based transportation modes should be preferred could rage on due to unaccounted externalities. Assuming that a ground transportation option is desirable, a range of current options is reviewed here, to better understand their cost structure and service characteristics.
The Private Auto

In North America at least, the private auto is by far the dominating form of intercity transportation, at least in terms of trip volumes. For person-trips between 100~499 miles, the private auto captured 93.7% of the market, while commercial airlines captured 2.3%, intercity bus 0.4%, and intercity rail 0.7% [1]. This automobile dominance is not limited to the rural areas. In the Northeast Corridor, where intercity rail service is well developed, the private auto nevertheless achieved a 72% market share between New York and Washington (Consolidated Metropolitan Statistical Areas), while airlines carried 22%, and rail 6% of all person-trips [2].

What explains this automobile superiority? There are a variety of reasons: (1) collective transportation requires either geographical or temporal consolidation, sometimes both, thus a high demand-density is needed; (2) other benefits are associated with having “your car” -- including easier freight carriage, the convenience factor, choice of schedules, etc.; (3) usage of the private auto is subsidized to different extents by the government than other modes of transportation; (4) the incremental cost per person is approximately zero, for the same origins and destinations.

For shorter trips in the 100~600 mile market, the access time is an important part of the total journey time, where the route structure could mean convoluted routings that make collective transportation unattractive. 55% of all passengers in New England drive more than 16 miles to an airport [3]; nationwide median distance for airport access is 21 miles [4]. These statistics suggest that with today’s North American metropolises, which are sprawled over large areas, the private auto has an important advantage in its totally-connected route network that collective modes will find difficult to surpass. Lu & Martland (2002) discusses the accessibility question in greater detail in a previous publication.

Intercity Buses

Common carrier intercity buses has all the disadvantages of collective transportation, but none of the speed or comfort advantages associated with the other modes. The statistics demonstrates this: despite a much wider route network than intercity rail, common carrier buses achieves only half the market share. Intercity buses tend to carry captive riders without access to an automobile, or choice riders with very low value-of-time whose major criteria is price. However, in some areas, the demand density is so low that the only intercity mass-transportation option is coach. While remaining an important element of rural public transportation in states such as Vermont, Maine, New Jersey, Ohio, Utah, New Mexico and Texas, the common carrier intercity bus is unlikely to be a serious contender for choice travellers in high-volume corridors.

Conventional Train

The conventional train is sometimes seen as a large bus. In the intercity sector at least, there aren’t many corridors in the world that would justify conventional train service on the basis of capacity alone. Bus service, on the other hand, could be much more flexible and offers much better access. The main advantages of the train is that it is able to offer hereto unparalled level of comfort and amenities, in addition to immunity from highway congestion and much higher speeds where infrastructure permits such operations. If the conventional train is unable to offer higher speeds than the intercity bus, it will be seen as simply a large bus and destined to fail even more miserably than the bus. On the other hand, if the train is able to distinguish itself from the automobile through a combination of higher speeds, better amenities, plus
immunity to congestion experienced at airports and on urban expressways, it would be the dark horse of intercity transportation.

Much research has already been done in making the conventional train more competitive through incremental upgrades. The current FRA Next Generation High Speed Rail Technology Demonstration Program is focused on four distinct areas: (1) positive train control; (2) high-speed non-electric locomotive; (3) high-speed grade-crossing protection; (4) high-speed track and structures (FRA, 2002). This is consistent with the incremental high-speed rail approach discussed in Roth (1994), where existing rights-of-way are retrofitted with technology enhancements to enable higher-speed operation of passenger trains.

This approach has several distinct advantages, compared to the other high-speed rail solutions: (1) it takes advantage of inherent value in existing railroad networks; (2) because of its phased nature, positive cash flows occur earlier in the investment cycle, providing financing for later stages; (3) due to the total backwards-compatibility of the equipment, high-speed trains are able to penetrate areas with lighter demand density on conventional infrastructure, resulting in a much wider route network than otherwise possible; (4) the comfort level and space available associated with conventional equipment is preserved -- a very important market consideration in the North American market.

The disadvantages of this approach are inherent in the paradigm: (1) because of the need to share track space with other trains operating as slowly as 30mph, dispatching trains efficiently becomes a major issue for speeds above 70mph or so -- track capacity for mixed speed traffic is much lower than that for traffic at a given speed; (2) the level of investment to reach a given speed could be higher, because of the additional safety precautions needed on a mixed-traffic railroad; (3) at higher speeds, conventional wheel-flange guidance systems become disproportionately expensive to maintain safely; (4) to cater for different types of traffic, the engineering parameters for track geometry are constrained by the least common denominators, making high performance for a particular traffic type difficult if not impossible to achieve.

High-Speed Trains

Pioneered by the Japanese Tokyo-Osaka Shinkansen in 1964, exclusive-guideway high-speed trains have always been seen as the silver bullet to the passenger rail problem by advocacy groups. What is often not appreciated is that the Tokyo-Osaka Shinkansen was justified not on the basis of increased performance, but as an alternative to four-tracking the Old Main Line (Yamanouchi, 2000). Even in traditionally exclusive-guideway systems, penetration into conventional trackage by high-speed rolling stock is usually considered an advantage, as doing so greatly enhances the accessibility of high speed services. During the first phase of the Paris-Lyons TGV, services extended beyond Lyon to provincial cities running on conventional infrastructure. In Britain, Intercity 125 sets operated on a scheduled basis to the north of Scotland, often operating over trackage that enabled a maximum speed of only 45mph. Such “penetration” by Shinkansen trains was impossible in Japan due to the existing narrow-gauge infrastructure.

The fundamental problem with high-speed trains remain the high cost of infrastructure. On high-speed track structure, gradient is practically limited to about 3%, and there are strict standards on curvature, length of transition, cant and cant deficiency, as well as tolerances in track gauge, track level, and axle-loads. For a mixed-traffic railroad, these constrants are even more severe: gradient is limited to about 2%, cant about six inches, and curvature limited by the highest speed passenger train that is designed to operate over it. These engineering constraints are not a major problem on the prairies, where the costs of laying straight track may simply be associated with buying out specific farms. In mountainous territory, however, these engineering constraints may increase (in a non-linear fashion) both mileage and the amount of rock blasting required.
On the Usui Pass between Tokyo and Nagano, relaxing the maximum permissible grade from 2.5% to 6.7% would halve the construction expenses from ¥7.1 billion to ¥3.6 billion, while decreasing distance from 16 miles to 7 miles and drastically reducing the curvature required (Yamanouchi, 2000). Similar experience was found while constructing transcontinentals in North America. Many cut-offs were later built to reduce operating costs and transit times on originally curvaceous and heavily graded mainlines. In most cases, the revised alignment was more expensive and only made possible through reinvesting revenues generated by earlier traffic.

Magnetically-Levitated Trains

Magnetically-levitated trains is the ultimate in exclusive-guideway technology. Instead of using steel-wheels on steel-rails to provide support and guidance, maglev use magnetic forces to accomplish the same. Vehicle bodies are slightly elevated above the track structure with magnetic repulsion to eliminate any contact resistance, while the train is both pulled and propelled forward with magnetic attraction and repulsion, generated by fixed superconducting magnets buried into the track structure.

Maglev was designed to be a high-cost, high-performance system worthy of the space age. However, the high costs of creating a brand-new right-of-way in an urban area (where the demand density is sufficiently high to justify high speed rail), and the inherent high costs of superconducting magnets has limited its potential. Commercial implementations of maglev have been limited to very-short distance, transit-like applications, usually proposed as a non-stop, ultra-high speed link from an airport to the downtown area -- playing a similar role to that proposed for the tiltrotor aircraft 20 years ago. The only commercial implementation to date has been one 17-mile link between downtown Shanghai and its airport in China (Blow et al, 2003).

Maglev has the high per-mile costs of fixed-guideway technology, while being unable to share that cost with any other type of traffic due to its exclusive-guideway nature and lack of backwards compatibility. Applications of maglev, at least in its purest form, is likely to be limited to very-short distance markets where use of aircrafts is infeasible, and where the journey time difference between ten and 30 minutes is able to justify billions of dollars in right-of-way costs.

However, because of the enhanced technical characteristics of maglev, several possibilities have been raised that were not previously available to high-speed fixed-guideway transits. Because maglev technologies does not rely on adhesion, maglev trains are able to negotiate at very high speeds curves and grades (up to 10%) that are comparable with interstate highway engineering standards. This raises the possibility of putting maglev-type infrastructure along highway alignments, reducing costs and potentially allowing more direct alignments. The Baltimore-Washington maglev (BWMaglev.com, 2002) proposal is substantially based on placing an elevated maglev alignment over the existing I-95 Corridor. Nonetheless, the need for a brand new guideway could make any maglev scheme very capital intensive; about 53% of the projected costs of the BWMaglev are in the construction of the right-of-way, despite the existence of the interstate highway.

Strategy to Combat Automobile Dominance – Technology Needs

For collective intercity ground transportation to be successful, it must emulate the automobile as far as possible in terms of accessibility, retain the speed advantage of steel-wheel guidance, space and carrying capacity advantage of a railcar, while minimizing the cost of capital construction. In traditional service planning and design, the trade-off between speed and accessibility has often been represented as a hierarchy (see Van Nes, 2001). Higher-speed, limited-stop modes offers lesser accessibility, but make up for it
through shorter journey times. Van Nes suggests that when changing hierarchical levels, the higher-speed mode ought to travel at about three times the speed of the lower-speed mode. As seen in Figure 2, there may be a niche market between the automobile (extremely high accessibility at about 50mph), and the commercial airline (very low accessibility at around 550mph). In theory, the high-speed rail could succeed by offering better accessibility than the commercial airline at an average speed of 110mph, provided that the infrastructure costs remain under control.

![Figure 2: Intercity Rail’s Possible Strategic Positions on the Accessibility/Speed Plane](image)

In certain circumstances, where a travel corridor covers regions of high demand density (requiring three or more levels) and low demand density (requiring only two levels), it is conceivable that high-speed rail could transcend between levels without change of vehicle, simply by changing the station spacing between stops -- in the same way that an automobile would interchange between an interstate highway and a rural route without having to stop or transfer passengers. The critical business needs for intercity ground transportation therefore are:

- Reasonable infrastructure costs, especially over urban and mountainous terrain
- Comfort factor similar to a conventional train
- Fast acceleration to permit stop spacing of about two miles in urban areas
- Average speeds of about 110mph for most station pairs
- Both a line-haul and a distribution mode – transcend network layers without transfers

The technology needed resembles essentially an FRA-compliant subway car with a generous loading gauge that is capable of travelling at very high speeds (150~200mph) in the rural areas to achieve an average speed of 110mph while making multiple stops within an urban area. Although this appears to be a technology that is already available, part of the problem is the persistent high costs of making steel guideways support heavy vehicles travelling at speeds above about 100mph, and the engineering constraints in terms of curvature and vertical alignment that can dictate viable high-speed rail alignments, as already discussed.
Rapid Transit Technology Case Study – Relationship to High Speed Rail

In infrastructure-intensive systems, sunk investment plays a major role in determining what technologies are viable, given what has happened before. In the rapid transit industry, this has resulted in subways being maintained where its large carrying capacity is no longer needed. Successful technologies have mostly been designed to be backwards-compatible. In North America, the railroad network is extensive and represents considerable sunk investment. It is imperative for the success of high speed rail to leverage the value of existing infrastructure and rights-of-way, while maintaining freight access.

The Importance of Inherent Value in Existing Infrastructure

The effect of sunk investment on the economics of infrastructure-intensive systems is reviewed here. Historically, as technology progressed, newer technologies have not always replaced older systems. There are many examples: (1) Light rail is considered more cost-effective than heavy rail, although many cities continue to operate heavy rail systems constructed at the turn of the century; (2) The double-stack innovation in North American railfreight have generally not spread to Europe, due to the high costs of raising bridges and enlarging tunnels.

The common reason for these seemingly backwards decisions are the same. The value inherent in existing infrastructure is so large that the new technology has no choice but to interface with the older technology. Economically efficient decision-making would allow the older technology to live out its ‘life-cycle’ while introducing new technology alongside it to provide enhancement and capacity relief at the most constrained points. In most cases, the new technology does not offer a sufficient performance boost to justify immediate replacement of the previous-generation technology at its current replacement value. Premature abandonment of assets has a very real economic cost associated with it. Only in rare cases where there is a performance step-change, would it be worthwhile. One such example is the wholesale replacement of diesel locomotives with D.C. traction motors in coal service during the late 1980s. Even in that case, the value of the scrapped D.C. locomotives are far from zero -- most were traded into the manufacturer to be reconstructed into A.C. units, or sold to shortlines to replace locomotives built in the 1950s.

There are examples outside transportation also: (1) Until recently, personal computers have been shipped with 4.77MHz ISA expansion slots which were developed by IBM in 1981, even though many different types of expansion buses have been developed since then. (2) Microsoft Windows continue to start a computer in 16-bit mode and with a memory limit of 640 Kbytes before loading a protected mode kernel to enable linear addressing, available in Intel hardware since 1984. In these examples, the replacement value is in terms of hardware peripherals built with the older interface, and software drivers already written assuming a 16-bit architecture.

Systems Engineering in Rapid Transit Applications

Systems Engineering is the discipline that studies the attributes of different technologies, and designing a system that may involve one or more technologies, to accomplish a desired goal in the most cost-effective manner. An example of a systems engineering question would be the choice of mass-transit technology with which to construct a transit line – and whether to build the line at all. Different parts of the same transit corridor might have different demand characteristics, thus the ‘optimal’ technology for different parts of the corridor might not be the same. A radial route around a city may traverse both an affluent low-density neighbourhood and a poor high-density neighbourhood with large demands and large number of captive riders. From a capacity standpoint, heavy rail subway might be most suitable for the high-density
neighbourhood, while a light-rail might be able to offer higher frequencies in a low-density neighbourhood to attract choice riders.

Here a logical solution might be to develop a hybrid scheme where some light-rail vehicles are able to inter-operate with the subway in the core section of the corridor, while providing a higher frequency to the lightly-travelled portions. With train-separation provided by coded-track circuits, special light-rail vehicles fitted with third-rail shoes and able to dock at high-platform stations, it is not necessary to split the radial corridor into two distinct lines to utilize the most appropriate technology for each section. The downside is that this flexibility could be more expensive than a totally segregated solution.

This is certainly not a new concept: the Everett-Dudley Main Line elevated (now the Orange Line) in Boston inter-operated with the Boston Streetcar Company between Boylston and Haymarket prior to the construction of the tunnel beneath Washington St., today's Orange Line central subway (see Moore, 1999). The Riverside branch of the Green Line was a former New York, New Haven & Hartford commuter rail line, and is today operated with electric streetcars but retains commuter-rail type station spacing, demand characteristics, and some element of rail-rapid type signalling. Hybrid-type schemes can work well because the incremental costs of creating a hybrid is usually small compared to the costs of new rights-of-way or applying the inappropriate technology for the sake of standardization. In the case of the Riverside branch, the bankrupt Penn-Central was able to realize the sale value of the four-track right-of-way between Brookline Jct. and CP-Cove (part of which became the Massachusetts Turnpike) by allowing the MTA to replace its commuter rail service with a streetcar service, thereby sharing the costs of downtown access infrastructure with the other Green Line branches.

*Applying the Rapid Transit Experience to High Speed Rail*

In transit, subway, streetcars and buses have been seen as distinctive modes with different characteristics. The example above suggests that in some circumstances, the modes could be made to inter-operate to allow different parts of the same corridor to be tailored to its demand characteristics, without necessitating a change of vehicle between different sections. In the same way, highway designs are tailored depending on the purpose of the link and geographical characteristics; the same automobile may travel over access roads, arterials, highways and interstate turnpikes all in a single trip.

Traditionally, conventional train, high-speed rail and maglevs have been seen as different modes. As already discussed, conventional rail and high-speed rail could coexist given suitable engineering parameters and sophisticated train-separation technologies that ensure safety. In a sense, tilting train is simply a technological reponse to the need to better adapt the high-speed rail vehicle to conventional rail infrastructure where the demand density is insufficient to justify all-out investment in a brand new alignment or realignment schemes to retro-fit conventional lines with sweeping curves.

Perhaps maglev should not be seen as a separate mode at all. The performance increase have been clearly shown not to justify the costs, at least for intercity corridors of more than about 30 miles in length. However, if maglev is seen as an add-on infrastructure component that could be applied to the most constrained locations on a conventional rail network, the economics become much more feasible. In the same way that railroad electrification is often done for high-density suburban commuter corridors where the high acceleration and higher reliability is vital to service delivery, railroad maglevication could be done for sections of track that meet one of the following conditions: (1) sufficiently high demand density justifies the high speeds on performance grounds alone; (2) the terrain is sufficiently difficult such that relaxing the gradient constraint would result in construction and substantial journey-time savings; (3) the existing urban
The Incremental Maglev and Maglevication Technology

The concept of incremental maglev is essentially very simple. Instead of building a dedicated guideway and dedicated vehicles, stations, facilities, and other such large capital items, magnetic guidance infrastructure is simply retro-fitted to parts of existing railroad network in a backwards-compatible fashion. This process will be termed ‘railroad maglevication’, in the same way that retro-fitting electric power distribution infrastructure (i.e. catenaries) to steam railroads is called ‘railroad electrification’.

The Incremental Maglev Vehicle (and Truck Assembly)

The vehicle is essentially a tilting conventional train with reengineered truck assembly that is capable of running on existing railroads, but enters an enhanced ‘magnetic’ mode when it encounters maglevified infrastructure. Truck technologies are already mature, and there are a number of design possibilities for an ultra-high performance truck: (1) active steering radial trucks could reduce rolling contact resistance beyond what is available from passive radial trucks currently used on EMD diesel freight locomotives; (2) higher wheel conicity than typical on current rapid transit vehicles would enable trucks to steer much more efficiently, especially on very tight curves and when running at very high levels of cant deficiency (or imbalance).

For the magnetic guidance system, several possibilities exist: (1) guidance magnetic plates could be fitted at a suitable position beside the rail, exerting magnetic repulsion on the wheel, the truck frame, or the vehicle body (see Figure 3, Options 1, 2, 3) on the outside of the curve; (2) propulsion magnetic plates could be fitted in the four-foot, between the running rails, to guide the truck by magnetic attraction (see Option 4), similar to the linear induction systems currently used on the Vancouver Skytrain and proposed for the New York JFK Airtrain; (3) propulsion and guidance magnets could be fitted on both or either side of the running rails (see Option 5 & 6), guiding the train with a combination of attractive and repulsive forces; (4) guidance magnets could be made to act directly on the middle and upper parts of the coach body (Options 7 & 8), providing both tilting and guidance functions; (5) a flexible contact guidance system could be developed in place of magnetic guidance. Clearly, more research would be necessary to identify the system with the lowest costs or the highest likelihood of success. Nonetheless, these proposals are much closer to existing knowledge and experience in truck design than pure maglev proposals, in addition to offering the advantage of backwards-compatibility.

With this design, it is possible to put all the intelligence on the vehicle. The track-bourne equipment could be permanent magnets or very strong electromagnets that are either on or off. Intelligence aboard the vehicle will adjust the polarity and strength of magnetic field generated by the vehicle-bourne magnet to give the necessary guidance forces for the speed at which the vehicle is travelling at that point. Conceivably, the vehicle could guide itself through a feedback system that measures the accelerating forces required and adjusts the on-board magnetic plates accordingly, given knowledge about the physical magnetic infrastructure available en-route. By putting the intelligence on the vehicle, the infrastructure costs per route mile could be kept to a minimum – an important factor in the success of intercity transportation systems with high route mileage and relatively small fleets.
Figure 3: Options for Locating Guidance Magnets
On Dual-Mode Incremental Maglev Vehicle

Engineering Feasibility

How feasible is this from an engineering perspective? Obviously, detailed engineering and design work would be required to answer that question. In principle, the concept is not ridiculous. Conventional rail is unable to achieve grades of more than 3% due to adhesion limitations. If the bogie frame was magnetically assisted by being dragged up a grade, the reaction forces at the wheel-rail interface remains constant, but the work required against gravity is reduced, as part of the work is done by invisible magnetic forces that act on the bogie frame independently of friction. Conventional rail is unable to negotiate sharp curvatures at high speeds due to the limited ability of the wheel flange to provide reaction forces for lateral acceleration. At locations with high rail cant, this force is augmented by the component of gravitational force that is parallel to the plane formed by the two rails. If the bogie frame was magnetically assisted by being repelled against a magnet on the outside of the curve, the required lateral acceleration to be provided by gravity and the wheel flange is reduced (see Figure 4). The bolster assembly would require considerable re-engineering, as it could no longer be assumed that gravity would hold the carbody on top of the trucks. Obviously, the trainset would also need to be designed with a low centre of gravity, or other stabilization features, to minimize the overturning risks at high levels of imbalance.
Figure 4: Forces available to accelerate the train around the curve is the sum of magnetic and reaction forces in an maglevified vehicle. Active or passive tilt systems addresses passenger comfort issues.

Signalling systems would prevent non-authorized trains from entering the maglevified cut-offs that could create a dangerous condition if non-maglevified vehicles were to enter. Maglevified cut-offs actually serve a natural purpose in regulating traffic. In a highly congested, mixed-traffic intercity corridor, passing high-speed passenger trains and coal trains may be problematic. Where a maglevified cut-off of about 20 miles in length is constructed, the older railroad by-passed essentially becomes a low-grade freight route. Since the slower coal trains are likely to take a long time to cover the ascent to the summit, the high-speed passenger trains using the maglevified cut-off could overtake the coal trains while they are in the low-grade loop. In urban corridors, commuter trains can conceivably benefit from the maglevified infrastructure through greater acceleration and therefore shorter time between closely-spaced stops (see also Lu, 2001).

Operation of Freight Trains Over Maglevified Trackage

Of course, maglevified sections of trackage that depend on the linear induction motor to prevent stall on a steep gradient would be incompatible with freight applications, although any trains fitted with maglev trucks could in principle traverse the trackage (just as any train with pantographs may receive power from the catenaries while traversing electrified trackage). The design values used for the magnetic infrastructure could have interesting implications for the operation of freight trains. On gradient-limited portions of maglevified lines, only a portion of cars are required to have magnetic trucks – provided the 200,000 lbs knuckle load limit is not exceeded at any point along the consist, and that the weight of the consist could be supported by those trucks within the consist that are magnetic. It is possible that a maglevified locomotive would be able to tow ordinary freight cars over the maglevified route, although this is unlikely to be economic except for highly time-critical freight. On curvature-limited portion of maglevified lines, any train may traverse maglevified trackage, but only trains that are completely maglevified on every truck would be able to traverse it at the higher speed permitted for maglevified traction on that section of the railroad, since high levels of cant deficiency without magnetic assistance could result in derailment risks.
The operations of freight trains have always been a highly skilled discipline. Geographic familiarity in terms of gradients, maximum authorized speeds, and other infrastructure constraints have been required for freight train crews since the early days of railroading. The addition of knowledge of maglevified infrastructure, and the necessary calculations of magnetic versus adhesive tractive effort available from given types of traction (and consumed by given types of freight cars) would complicate matters, but with increasing portability of computer systems it is possible for these complex calculations to be performed on-

Figure 5: Sample System Timetable for a Maglevified Line
the-fly with onboard intelligence as part of the train control and regulation system. How the system timetable might look, to convey all necessary information about the maglevified infrastructure, is shown in Figure 5.

The Technology: Would it Stick?

Whenever novel ways to approach engineering is proposed, there is inevitably a forest of criticism suggesting why it wouldn’t work, citing previous experiences that have failed to accomplish their goals. One example frequently mentioned is the proposal to attach retractable rail trucks to buses so that buses could also operate on rail rights-of-way. The fundamental reason why railbuses failed to take off have very little to do with engineering: track maintenance crews on railroads routinely use hi-rail vehicles, which are designed for both highway and railroad use. The reason the railbus did not succeed is because allowing buses to run on rails offered very little benefits. Buses operating on interstate highways can achieve almost as high speeds as buses operating on railroads, thus railbuses offered little differentiation from highway-only buses.

In the case of the hybrid maglev-HSR vehicle, maglevs clearly offers a significant speed advantage, plus considerable infrastructure cost savings at certain locations compared to a rail only vehicle. These costs and benefits are analyzed in greater detail in the next section.

Cost-Effectiveness of Railroad Maglevication

To assess the cost-effectiveness of the incremental maglev proposal, a typical intercity corridor is considered in terms of journey time performance, construction investment costs, and cost-per-minute-saved as a cost-effectiveness measure. The typical corridor is 210 miles in length, consisting of five stops each in two large metropolitan area at either end, and two intermediate nodes at mileposts 70 and 150. The metropolitan-area stops are spaced at two-mile intervals. The typical corridor is further divided into five subdivisions: City, Prairie, Mountain, Seaboard, and Metropolitan. The Metropolitan Subdivision hosts extensive commuter rail services that share a corridor with the intercity service. The Seaboard Subdivision features three major bridges and many curves, limiting speed of conventional operations to 79mph. Mountain Subdivision features one major mountain pass and two tunnels, the resulting curvature and gradient limits speed of conventional operations to 60mph. Prairie Subdivision features featureless plains and farmland which allows bee-line construction of conventional lines that allows unimpeded 110mph operations. The City Subdivision features similar urban constraints, limiting speed to 60mph, but without commuter rail service.

The detailed assumptions for the typical corridor is given in Table 1.

<table>
<thead>
<tr>
<th>Subdivision</th>
<th>Begins</th>
<th>Ends</th>
<th>Speed (Conventional)</th>
</tr>
</thead>
<tbody>
<tr>
<td>City</td>
<td>MP 0.0</td>
<td>MP 20.0</td>
<td>60 mph</td>
</tr>
<tr>
<td>Prairie</td>
<td>MP 20.0</td>
<td>MP 105.0</td>
<td>110 mph</td>
</tr>
<tr>
<td>Mountain</td>
<td>MP 105.0</td>
<td>MP 140.0</td>
<td>60 mph</td>
</tr>
<tr>
<td>Seaboard</td>
<td>MP 140.0</td>
<td>MP 190.0</td>
<td>70 mph</td>
</tr>
<tr>
<td>Metropolitan</td>
<td>MP 190.0</td>
<td>MP 210.0</td>
<td>70 mph</td>
</tr>
</tbody>
</table>

Table 1: Assumptions of Geography for a Typical Intercity Corridor

The base case is a conventional express service that currently connects the two cities at slightly below the posted speeds (due to station stops and other speed restrictions such as that associated with bridges and switchwork). The trip currently takes just over three hours, resulting in an average station-to-station speed of 70mph -- only slightly better than the private auto, and the majority of people drive between the cities.
The journey time resulting from each type of upgrades was compared to the base case to ascertain the time-savings, while a typical cost-per-mile for the type of infrastructure and the type of terrain was used to calculate the likely costs. The cost-effectiveness measure was then calculated. Although this is a surprisingly simple methodology, it is extremely powerful, and can differentiate between the sour lemons, the silver bullets, and the marginal cases that warrant detailed modelling and assessment work.

![Graphic Representation of a Typical Corridor](image)

**Figure 6: Graphic Representation of a Typical Corridor**

This type of cost-effectiveness analysis, where technological alternatives are compared in terms of their benefits, costs, and likely impact in terms of performance (often modelled using a customer utility measure), is Step 3 of the Performance-Based Technology Scanning framework (see Figure 1). Railroad maglevication was one of the more promising ideas identified using this method. Other technological ideas analysed are detailed in a separate working paper (Lu & Martland, WP-2002-03).

**Traction Performance Modelling**

In the City and Metropolitan Subdivisions, a key issue is whether maglevification will truly enhance the performance of the metropolitan distributor, where station spacings of around two miles is required to maintain access competitiveness with the private auto and thus continued running a very high speeds are impossible. Using a traction performance model that calculated sectional running times based on installed power, rolling contact resistance, consist weight, and calibrated using British Rail traction performance data, it was determined that on flat terrain, the best-performing conventional traction will reach a top speed of about 70mph between two stations spaced two-miles apart, taking approximately 150 seconds. On the other hand, a consist with performance characteristics more consistent with maglev-type traction will reach a top speed of 115mph, and travel the same distance in about 100 seconds. The likely time saving for our assumption of five stations per metropolitan area is therefore about four minutes.

This result has more implications for commuter rail than intercity rail. Many commuter rail lines feature ten or more stops. Daily round-trip time saving for travel from the outer suburbs could be as much as 18 minutes per day with maglevification. This time saving is very significant for a daily commuter, and for the commuter operator.

This result is sensitive to station spacing. Instead of assuming five uniformly-spaced stations, if stations for the City Subdivision were located at MP 0.0, MP 8.0, MP 10.0, MP 12.0, MP 20.0 to describe the typical configuration of Park & Ride stations in the exurbs with three downtown distribution stations, the time-saving of maglevication could be about six minutes. However, because of the relatively short distances...
involved between stations, maglevication could not realize its full potential, as no extended running at very high speeds take place.

**Mountain Railroading**

In the Mountain Subdivision, the key issue is whether maglevication would deliver the required cut-off offering time savings and higher speeds. In typical mountain terrain, if gradient constraints were relaxed, analysis of topological maps of Maryland revealed that a mileage savings of 20%~40% may be possible (the Usui Pass at 56%, was an extreme case). For the purpose of the case study, it was assumed that the construction of a 10-mile maglevified cut-off would reduce the total mileage of Mountain Subdivision from 35 miles to 30 miles. Maximum permissible speed on the cut-off would be 125mph. Using the traction performance calculator, assuming an entry speed of 70mph, the maximum speed achieved on the maglevified cut-off would be 125mph, achieved two-miles into the cut-off. Due to the gradient considerations, 125mph may not be actually achievable within that distance, although with a 10-mile cut-off and presumably a considerable downhill section, at least 5-mile of the cut-off could be assumed to be cruising at 125mph.

Based on these assumptions, journey time over the ten-mile cut-off would be about 350 seconds, compared to the base case of 900 seconds (15-miles @ 60mph). The total journey time saving achieved is therefore 9 minutes. If speeds were unconstrained for the cut-off, the train will reach a top speed of about 180mph, traversing the cut-off in 250 seconds, achieving a total journey time saving of 11 minutes.

**Coastal Railroading**

In the Seaboard Subdivision, since gradient is not a constraining factor, it is conceivable that maglevication is only necessary where there are severe reverse curves. In addition, some economies are possible since maglevication is only necessary for those sections of track where realignment would be required to handle conventional traffic at high speeds. It is incorrect to consider only those sections of trackage affected by maglevication, since removal of severe permanent speed restrictions due to curvature could enable higher actual trains speeds to be achieved in neighbouring sections where the train is unable to make use of available line speeds due to acceleration characteristics. In this study, it was assumed that 40% of non-contiguous trackage in the Seaboard Subdivision required maglevication to handle trains travelling at 110mph, while the other sections will handle 110mph using conventional techniques and with very little track realignment work. Thus the result of upgrading 20 miles of track is to enable trains to travel over the Seaboard division at an unimpeded 110mph, except the permanent speed restrictions associated with the structures.

Based on these assumptions, journey time over the Seaboard Subdivision would be about 1,800 seconds, compared to the base case of 2,600 seconds. The total journey time saving achieved is therefore 13 minutes or so. If the structural constraints could be removed, the journey time savings would be 16 minutes. If the entire Seaboard division could handle trains operating at 125mph, the journey time saving would be 19 minutes.

It is likely this technique could also be applied to the portion of Mountain Subdivision not affected by the cut-off, generating further time savings. Using this method, if Mountain Subdivision required maglevication for 60% of all track miles to achieve 110mph operating speeds in the section of track not by-passed with the cut-off, an additional eight minutes of the time savings would be possible.
**Benefit Analysis**

Using the most aggressive version of the schemes discussed in the previous section, the total journey time saving over the 210-mile trip would be 50 minutes. Using the least aggressive version, the total time saving would be about 30 minutes. Utilizing a similar methodology, journey time saving estimates was made with reasonable assumptions, for a variety of investment and upgrade options. The results are presented in Table 2. It was assumed that maglevication would not achieve savings in the Prairie Subdivision beyond conventional methods.

<table>
<thead>
<tr>
<th>Division</th>
<th>Minute Saving by Investment Alternative</th>
<th>Hybrid</th>
<th>Hybrid</th>
<th>Conventional</th>
<th>HSR</th>
<th>Maglev</th>
<th>Maglev</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Best Case</td>
<td>Conservative</td>
<td>New Line</td>
<td></td>
<td>New Line</td>
<td>Port to Port</td>
</tr>
<tr>
<td>Seaboard</td>
<td>19</td>
<td>11</td>
<td>5</td>
<td>9.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mountain (cut-off)</td>
<td>11</td>
<td>9</td>
<td>—</td>
<td>—</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mountain (realign)</td>
<td>8.5</td>
<td>0</td>
<td>5</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prairie</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>14.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>City</td>
<td>6</td>
<td>4</td>
<td>—</td>
<td>—</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metropolitan</td>
<td>6</td>
<td>4</td>
<td>—</td>
<td>—</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>50.5</td>
<td>28</td>
<td>10</td>
<td>34.1</td>
<td>96</td>
<td>43.5</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2: Results of Benefit Analyses for Different Route Improvements Technologies**

Purely from the perspective of journey time savings, obviously the highest-technology option (new maglev line) achieves the highest speed and the most time savings. Given the relatively high speeds in the existing conventional railroad corridor, it is not clear that a new, dedicated high-speed rail line could achieve much time savings, even though the new alignment in the Prairie Subdivision was designed for 150mph operations. The time savings available with the maglevication option depends to a large extent on the aggressiveness of combining maglevication with conventional realignment methods, but it is clear from the above analysis that the time savings are in the order of a new dedicated high-speed rail line – not as good as a new maglev line, but better than simple realignment and re-engineering. The port-to-port maglev does not save nearly as much time as the downtown-to-downtown maglev once access time and transfer time has been taken into account.

The hypothetical corridor under current discussion is typical of North American rail corridors: capacity issues can be addressed without new infrastructure, thus the Tokaido Shinkansen type of benefit is unlikely to be seen – all benefits accrued are in terms of reduction in trip times. In the next section, cost-effectiveness of the upgrade is considered in terms of investment cost per time saved.

**Cost-Effectiveness Analysis**

To assess the costs of construction, some typical cost figures from publicly available industry sources were used. The cost of maglevication was assumed to be similar to the cost for track and structures in recent cost estimates for maglev proposals. The 40-mile BWMaglev project is costed at $3.7 billion -- $93 million per mile, 53% ($49 million) of which is in the guideway structure. A significant proportion of that cost is in the elevated structure, which maglevication of existing trackage would not require, thus $30m per mile seems a reasonable figure. Using the assumptions described in the above discussion, a cost model to estimate the cost of different investment alternatives was created. In essence, the cost model separates the cost of realigning, maglevifying existing infrastructure, and constructing new rights of way. A representative run of the model is shown in Table 3.
Table 3: Representative Run of Rail Route Improvement Cost Model

Using this (admittedly primitive) model, the costs and cost-effectiveness for different investment alternatives were evaluated. The average cost-per-mile clearly reflects the relative costs of the different technologies, with conventional route improvements being the cheapest option and the city-to-city maglev being most expensive, due primarily to the costs of constructing new rights-of-ways (or constructing elevated viaducts or tunnels over existing highway corridors) to provide downtown and suburban access. However, the cost-per-mile does not trade off investment against performance. The cost-per-minute-saved is a better cost-effectiveness measure and a better proxy for the likely cost-benefit ratio of the technology. The results in Table 4 show that conventional route improvements and maglevication are roughly equally as effective in terms of cost-per-minute, although obviously much greater savings are available with maglevication than with conventional methods alone. Although savings associated with dedicated maglev is substantial, the costs are a lot higher. It is only half as cost-effective as the incremental schemes where the capacity of existing rights-of-way is not constrained.

Table 4: Cost-Effectiveness of Maglevication Versus Other Methods of Route Improvements
There are two most notable features of this table: (1) different methods of route improvements may yield an alignment of different length, due to the engineering and cost contraints of the chosen technology; (2) the new maglev travelling between remote Park & Ride lots on the outskirts of the metropolitan area is the least cost effective of all options, since maglev offers little advantage in the wide open spaces of Prairie Subdivision, and the transfer time required from a local mode to the high-speed mode could negate much of the time savings. In high-speed rail, access to the urban neighbourhoods, suburban business districts, and the downtown, can be a constraining factor.

Other Implication of Maglevication Versus New Alignment Construction

From a project evaluation perspective, the beauty of maglevication lies precisely in the fact that it is incremental in nature. At discount rates of 7% to 8% typically used for public sector projects where tax increases may be necessary for its financing, the need to achieve significant benefits within the first few years of the project is important. Large projects are extremely difficult to justify, because of the huge debt burden incurred initially. The new alignment options, whatever the technology, is the typical ‘big project’ where large costs are incurred up front and the revenue stream builds up slowly over the life of the project. The route improvement and maglevication approaches are incremental, where smaller projects could be carried out in a number of phases, reducing the debt burden. Although the dual-mode maglev/conventional vehicles could be as much as three times the cost of a straight high-speed electric set, the immediate pay-off would be the tilting capability which enables marginally faster journey times, and very high speeds that becomes available as each piece of maglevified infrastructure come on-line. In any case, vehicles are a small proportion of the total cost of an intercity high-speed rail scheme. If those vehicles could be constructed on a rolling basis and phased into the existing fleet, the debt burden of the project could be kept manageable, in line with a pay-as-you-go incremental high speed rail plan.

Discussion

The main uncertainties facing the incremental maglev proposal are twofold: (1) whether adaptation of magnetically-levitated technology to a purpose for which it was not originally designed would work; (2) given that the technology works, whether maglevication of existing railroad trackage could be achieved at a cost of $30 million per mile. $30 million per mile may seem like a lot of money, but in addition to the fixed magnets that are required, the associated civil and realignment works, sophisticated signaling systems would also be necessary to regulate coal traffic at running at 30mph, perhaps regular passenger trains at 79mph, as well as maglevified vehicles capable of running at 125mph and above. In this case, sensitivity analyses reveals that the costs of maglevication must exceed $70 million per mile for the new conventional high speed rail alignment alternative to rank with maglevication in terms of cost effectiveness. At $70 million per mile, it is likely that an incremental approach to constructing a new conventional alignment (by progressively building cut-offs of constrained sections) may be a cheaper alternative than maglevication.

Quite clearly, the performance of incremental maglev will depend to a large extent on the terrain. For an intercity corridor comprising entirely of geographical features similar to the Prairie Subdivision, it is likely that neither tilting trains nor maglevication will achieve much. However, in that type of corridor, common in the Midwestern plains, conventional methods of route improvement, such as the positive train control schemes currently being tested in Michigan, is perfectly adequate – at least for speeds of up to 150mph. Unless ultra high speed is desired, maglev or maglevication may have little role to play. In intercity corridors that lie either along a coastline, or cuts through mountains, curvature is almost unavoidable, and the benefits of maglevication are most significant. There is a limit (either in engineering or financial terms) to what could be accomplished through construction of sweeping curves and applying ever greater degrees of rail
cant, especially in territories with significant reverse curvature. Maglevication could be the logical extension to the tilting train, conquering curves at ever higher speeds.

In worldwide terms, human population have traditionally congregated along the coastline, because of the important role of steamship in transportation from the 16th to the 18th centuries. Passenger railroads over wide open spaces have tended to be fairly rare except in North America. In Japan, Korea, Taiwan, the Southeastern coast of China, Britain, Sweden, Norway, the Rhine Valley, the Alps, and other similar locations, there are great demands for efficient transportation in congested urban, coastal and mountain corridors. Although maglevication would not be economically justifiable everywhere, especially where the passenger value-of-time is low, for the most common geographical features and demand characteristics, it is likely that maglevication would be a better alternative than either a new maglev alignment, or a new conventional high-speed rail alignment. The only exception to this are in locations where existing rail lines are already heavily congested.

**Conclusions**

In this paper, we have used some reasonable assumptions based on planning principles and engineering experience to demonstrate that if magnetically-levitated technology could be applied to conventional railroad equipment at a reasonable cost, the incremental maglev proposal offers better cost-effectiveness than either the exclusive high-speed rail or the exclusive maglev right-of-way options. The incremental maglev would take advantage of magnetic forces generated by large magnets to hold the train in place (and enable higher speeds without derailment) while a conventional train travels around a series of sharp reverse curves, and to assist conventional trains to climb sharp grades which wheel-rail adhesion alone cannot accomplish.

The basic premises underlying these planning assumptions are that: (1) accessibility to high speed rail within a large metropolitan area is important; (2) door-to-door journey time is more important than point-to-point travel speed. The basic engineering assumptions are that: (1) high-speed rail corridors travel over different types of terrain and incurs different type of engineering costs; (2) the cost of providing the right-of-way, including land and/or air rights acquisition, is independent of the cost of providing the guideway technology (i.e. railroad, or maglev). These are not unreasonable assumptions, although in some cases the choice of guideway technology would constrain the available choices of rights-of-way.

Analysis of a hypothetical corridor with typical geographical features of a high-speed rail corridor in the United States demonstrates that under those circumstances, incremental maglev is at least twice as cost-effective in terms of investment costs per journey time saved than either the dedicated high-speed rail and the dedicated maglev options. The cost-effectiveness of incremental maglev was found to vary fairly strongly with the terrain. The conventional high-speed rail (or other methods of route improvement involving limited realignments and deviations of existing rail routes) was most effective over wide-open spaces, while the incremental maglev is most effective over mountainous territory and near bodies of water, where reverse curvature are commonplace. As most heavily populated rail corridors are near bodies of water, incremental maglev represents a very attractive technology which offers better performance than conventional methods without resorting to the high costs of brand new alignments. In a situation where the existing rail corridors are not already congested with low-speed traffic, maglevication represents a technology option worthy of further study and engineering research.
References


Yamanouchi, Shuichiro. If there were no Shinkansen. International Department, East Japan Railway Company, Shibuya-ku, Tokyo, Japan (2000).


Appendix: Demand Sensitive Cost-Effectiveness Analysis for Railroad Maglevication

As a teaser for possible future economic analysis work, a demand-sensitive cost-effectiveness analysis was carried out for railroad maglevication as applied to the intercity passenger market. Railroad maglevication at $30 million per route mile was found to be far more cost-effective in terms of cost-per-passenger-mile and cost-per-passenger-trip than the new alignment alternatives, but slightly less cost-effective than the conventional route improvement alternative. This is not surprising, as diminishing returns are likely in the quest for ever higher speeds.

The results from this model should be treated with caution. Firstly, the $30 million figure has not been verified with engineering research, and will substantially affect the cost-effectiveness vis-à-vis the conventional realignment method. Secondly, the assumptions made in the demand model were extremely, exceedingly, almost pompously simplistic. Better demand models that are sensitive to fares, competition by the other modes, and other such factors, will deliver different conclusions for different circumstances. In this appendix, an exposition of this simple demand-sensitive model is provided, in the hope of stimulating further research interest in the topic.

Market Share Model

The market share model is essentially a simple Gaussian distribution with mean and standard deviation that varied with the distance between markets. It was not based on any survey data, and was calibrated according to author’s experience. In essence, at low mileages, automobile competition is likely to be dominant, and thus increasing train speed would do very little to woo passengers who are probably looking for lower access time. Thus, an asymptotic value for the cumulative Gaussian distribution is set according to the distance between markets. In this sort of market, people who take trains are likely to be choosing trains for reasons other than speed, thus the distribution is likely to be quite flat, with a large standard deviation with respect to speed.

![Market Share Projections](image)

**Figure 7:** Market Share Projections w.r.t. Corridor Length and Speed, Simple Model
At higher mileages, airline competition is dominant, thus increasing train speeds would help, but nothing would happen unless train speed exceeded a certain threshold value—presumably where the door-to-door time by train is become competitive with door-to-door time by air. However, the distribution is likely to be much narrower, with all passengers switching to train if the effective train speed exceeded the effective airline speed by a long way (e.g., Paris-Lyon, Tokyo-Osaka, London-Birmingham). Thus, the demand model was calibrated to reflect this set of assumptions, using four variables: mean, sigma, base_asym, and asym_div. The resulting demand curves are reproduced in Figure 7, and appears vaguely consistent with expert opinion.

**Ridership Model**

The Ridership Model is also very simple. It is essentially a two-variable gravity model (population and distance), calibrated using a few single data points from the American Travel Survey. The traffic carried by the train is then the total demand (from the gravity model) multiplied by the mode share (from the market share model) at the average speed generated by a specific investment alternative. Thus, in the 210-mile base case, the market share would be the market share captured by the train at 70mph in a corridor about 200 miles in length (i.e., 4%). A representative run of the ridership model is shown in Table 5.

<table>
<thead>
<tr>
<th>Ridership Analysis for Maglevicaiton</th>
<th>Lexie Lu, MIT Center for Transportation &amp; Logistics, 31/05/03</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discount Rate %</td>
<td>7% (from Summary Sheet)</td>
</tr>
<tr>
<td><strong>210 miles (Base Scenario)</strong></td>
<td><strong>Cost/mile</strong> Distance</td>
</tr>
<tr>
<td>Investment Alternative</td>
<td>($m/mile) (miles) (minutes) (minutes) (mph) (Look Up)</td>
</tr>
<tr>
<td>Base Case</td>
<td>0</td>
</tr>
<tr>
<td>Aggressive Maglevicaiton</td>
<td>12.9</td>
</tr>
<tr>
<td>Conservative Maglevicaiton</td>
<td>8.2</td>
</tr>
<tr>
<td>Conventional Route Improvements</td>
<td>3.1</td>
</tr>
<tr>
<td>Conventional HSR New Link</td>
<td>18</td>
</tr>
<tr>
<td>Maglev New Link, City-Metropolis</td>
<td>58</td>
</tr>
<tr>
<td>Maglev New Link, Magport-Magport</td>
<td>43.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5: Sample Ridership Analysis for Different Investment Alternatives</th>
</tr>
</thead>
</table>

To calculate the cost per passenger, an annuity method was used at a discount rate of 7%. It was assumed that the cost per passenger is at least the annual payment on the cost of the incremental upgrade, amortized over a long time (~30 years), divided by the annual ridership. This yields a lower-bound on what the ticket prices would have to be to make a profit.

In this particular case, although the Maglev New Link option clearly achieves the highest market share and highest market share gain, it does so at twice the investment cost per passenger trip of the conventional route improvement option, and 1.5 times the cost/trip of the aggressive maglevicaiton option. Although the
conventional route improvement achieves the lowest investment cost per passenger mile, the model doesn’t even register any ridership increase (thus the cost per new rider could not be calculated).

The Verdict

In terms of cost-per-passenger mile, maglevication is generally twice as expensive as conventional route improvements. However, maglevication is still half the cost (per passenger mile travelled) of a new high speed rail alignment, and quarter the cost of a new maglev alignment, and eighth of the cost of a maglev alignment that only went from magports to magports. These results are shown in Table 6.

<table>
<thead>
<tr>
<th>Demand-Sensitive Cost Effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lexcie Lu, MIT Center for Transportation &amp; Logistics, 31/05/03</td>
</tr>
</tbody>
</table>

| City Size | 2,000,000 |
| Discount Rate | 7% |

<table>
<thead>
<tr>
<th>Cost per Passenger Mile</th>
<th>Corridor Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment Alternative</td>
<td>50 miles</td>
</tr>
<tr>
<td>Base Case</td>
<td></td>
</tr>
<tr>
<td>Aggressive Maglevication</td>
<td>$0.91</td>
</tr>
<tr>
<td>Conservative Maglevication</td>
<td>$0.80</td>
</tr>
<tr>
<td>Conventional Route Improvements</td>
<td>$0.41</td>
</tr>
<tr>
<td>Conventional HSR New Link</td>
<td>$1.54</td>
</tr>
<tr>
<td>Maglev New Link, City-Metropolis</td>
<td>$2.86</td>
</tr>
<tr>
<td>Maglev New Link, Magport-Magport</td>
<td>$3.34</td>
</tr>
</tbody>
</table>

Table 6: Cost per Passenger Mile for Different Geographic Assumptions and Technological Investment Alternatives

If the assumption is that there is severe airline price competition and that the railroad is a price-taker in the express passenger market, then it is possible to calculate the carrier profit potential given geographic assumptions and technology assumptions. In the analysis shown in Table 7, the air-fare between two points was assumed to be $150 flat, regardless of mileage. With these assumptions, except in the case where there are three cities of 2 million population each, spaced 50 miles apart on a straight line (the 50+50 miles alternative), the new conventional and maglev links would require substantial decrease in the cost of technology to cover the costs of investment. In the 50-mile corridor, 100-mile corridor, and 50+50 configuration, maglevication and conventional route improvement could at least cover the costs of investment (although it is not clear whether they will cover the cost of operations).

Table 7: Carrier Profit Potential Assuming a Ticket Price of $150

These results are not set in stone. There are a lot of quick-and-dirty assumptions in these models, some unsubstantiated. The readers should develop their own models and reach their own conclusions.

ENDS