COMPARISON OF HIGH-SPEED RAIL SYSTEMS FOR THE UNITED STATES

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LIST OF ABBREVIATIONS

ARRA	American Recovery and Reinvestment Act
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
HSGT	High-Speed Ground Transportation
HSR	High-Speed Rail
Maglev	Magnetic Levitation
MCDM	Multi-Criteria Decision Making
PRIIA	Passenger Rail Investment and Improvement Act

SUMMARY

After decades of standstill in intercity passenger rail in the United States, the Obama administration recently started major initiatives to implement high-speed ground transportation projects that are expected to improve the nation's transportation system significantly, addressing most prevailing issues like congestion and energy prices while having positive effects on the economy.

This study evaluates and compares two high-speed ground transportation systems that have the potential to improve intercity passenger transportation in the United States significantly: the wheel-on-rail high-speed system and the high-speed maglev system. Both high-speed ground transportation systems were evaluated with respect to 58 characteristics organized into 7 categories associated with technology, environmental impacts, economic considerations, user-friendliness, operations, political factors, and safety. Based on the performance of each system in each of the 58 characteristics, benefit values were assigned. In order to weight the relative importance of the different characteristics, a survey was conducted with transportation departments and transportation professionals. The survey produced weighting factors scoring each of the 58 characteristics and the 7 categories. Applying a multi-criteria decision making (MCDM) approach, the overall utility values for either system were calculated based on the benefit values from the systems comparison and the weighting factors from the survey.

It was shown that the high-speed maglev system is generally slightly superior over the wheel-on-rail high-speed system. Because the magnitude of the difference in the

overall performance of both transportation systems is not very big, it is recommended that every project in the high-speed intercity passenger transportation market consider both HSGT systems equally.

CHAPTER 1

INTRODUCTION

1.1. Context and Purpose

Railroads in the United States have a long history. In the mid-19th century, the railroads provided connections between the frontier and the emerging United States. Railroads determined where new cities would be founded, becoming an important factor for economic and social development. At the beginning of the 20th century, almost all intercity passenger trips were by rail. Many “high-speed” trains were in operation in the years that followed. There were railroads in Wisconsin that reached speeds of 115 mph as early as 1936. By the early 1950s, half a dozen railroads ran trains at speeds of 100 mph. However, the passenger rail business faced significant challenges in the late 1950’s and 1960’s. Competition with the automobile and airlines caused many of the most profitable lines to lose money. In addition, both automobile and air travel benefitted from taxpayer support (Schwieterman, 2007, p. 13). The interstate highway system, for example, was built with a 90 percent share funded by the federal government.

With almost all private passenger rail companies out of business by 1971, Congress created Amtrak as a federally-owned company. Since Amtrak’s start, federal involvement in funding intercity passenger rail has mainly consisted of capital and operating subsidies annually appropriated from general funds (GOA, 2010b, p. 3). As opposed to the interstate highway system that is funded by motor fuel taxes, there has been no dedicated funding source for passenger rail in the United States. Vuchic and Casello (2002, p. 37) note that “the government and Congress consider[ed] minimizing operating assistance to intercity passenger railroad services (i.e. Amtrak) more important than maximum passenger attraction.” This is one reason why automobiles and air travel serve most of the intercity passenger market in the United States – in some corridors, their market share is up to 97 percent (Liu & Deng, 2004, p. 19).

Today, Amtrak operates a nationwide rail network that serves about 500 destinations in 46 states on 21,000 miles of routes and employs about 19,000 people (Amtrak, 2007, p. 1). America's only recent step into the high-speed rail business has been the introduction of the Acela Express in the Northeast Corridor in 2000. The Acela Express is the fastest train in North America, running between Boston and Washington D.C. and reaching its maximum speed of 150 mph on a 35-mile portion of its route between Boston and New Haven. On other sections between Boston and Washington D.C., the top speed is 135 mph (Amtrak, 2007, p. 5). Undulating tracks, a mediocre on-time performance, and relatively frequent mechanical problems, however, hinder the Acela Express from convincing the general public of the benefits of high-speed rail (Schwieterman, 2007, p. 14).

After decades of standstill in U.S. passenger railway systems, the Obama Administration recently instigated a new interest in the implementation of high-speed ground transportation systems. Shortly before President Obama took office, the Passenger Rail Investment and Improvement Act (PRIIA), enacted in October 2008, had set some foundations for high-speed rail as it provided about $4 billion over five years for three new intercity and high-speed rail grant programs and tasked states with setting up rail authorities to establish state rail plans for passenger and freight rail (GOA, 2010b, p. 3) (Dutton, 2010). After President Obama took office, high-speed rail became an even more important policy issue in transportation. Most prominently, the American Recovery and Reinvestment Act (ARRA), enacted in February 2009, dramatically increased federal funds for high speed intercity passenger rail from $120 million in fiscal years 2008 and 2009 combined to $10.5 billion available in fiscal year 2010 (GOA, 2010b). The $8 billion that the Recovery Act provided for these projects and another $2.5 billion in fiscal 2010 appropriations (Dutton, 2010) have attracted great attention from states and others who are planning to develop or improve intercity passenger rail service (GOA, 2010a, p. 1).

ARRA has established a new federal role in, and provided an unprecedented amount of federal funds for, intercity passenger rail. Thirty-seven states and the District of Columbia submitted 259 applications totaling approximately $57 billion for the $8 billion that ARRA made available (GOA, 2010b, p. 1) (GOA, 2010a, p. 2). In January 2010, the Federal Railroad Administration (FRA) announced that 62 projects in 23 states and the District of Columbia had been selected to receive the funds (GOA, 2010b, p. 7). The largest grant went to California ($2.34 billion) for the nation's most ambitious and most developed plan, a service between Los Angeles and San Francisco with speeds of up to 200 mph (320 km/h) that will later be extended to Sacramento and San Diego (GOA, 2010b, p. 7). This system enables passengers to travel from Los Angeles to San Francisco in less than three hours, or half the time it takes to drive (Rosenthal, 2010). Florida received $1.25 billion to construct an 84-mile-long high-speed track from Tampa to Orlando (Walsh, 2010) on which trains will be run at speeds of up to 168 mph by 2014. An extension to Miami is planned to be finished by 2017 (Rosenthal, 2010). These projects are, however, the only ‘true high-speed rail’ projects to receive funding from ARRA. Two other projects funded by ARRA (Illinois and Pennsylvania) are considered ‘high*er*-speed rail’, which means that speed is going to be upgraded to higher speeds than conventional rail, but not as much as to reach those speeds that are traditionally defined as ‘high-speed rail’ (see below). The high*er*-speed rail project in Illinois aims to increase top speeds to 110 mph for existing service between Chicago and St. Louis. With $1.1 billion, it received the third highest single grant from ARRA (GOA, 2010b, p. 7). The other 20 projects funded by ARRA, financially the major part of the grant program, are all conventional railway projects (GOA, 2010b, p. 8).

The purpose of this thesis is to examine and compare the technological options available for those high-speed ground transportation systems that have been referred to as ‘true’ high-speed rail, i.e. high-speed intercity passenger rail that reaches speeds of up to 300 km/h (186 mph) and higher. While conventional, lower-speed rail is another important part of an integrated, multi-modal passenger transportation system, this thesis focuses on *high-speed* ground transportation systems whose very goal it is “to increase the domain in which railway is the superior mode not only in convenience but also in speed or travel time (Vuchic & Casello, 2002, p. 34).” Besides high-speed ground transportation systems that are based on the classical wheel-rail interface (wheel-on-rail high-speed rail), this premise can also by fulfilled by another high-speed ground transportation system that is based on magnetic levitation: the high-speed maglev system. The goal of this thesis is to evaluate these two high-speed ground transportation systems based on the demands of the American intercity passenger transportation market.

1.2. High-Speed Ground Transportation Systems

Different authors have used the terms ‘high-speed ground transportation (HSGT)’ and ‘high-speed rail (HSR)’ in different ways. This thesis follows Liu and Deng (2004, p. 19) who stated that “there are two distinguished technologies under the high-speed ground transportation (HSGT) umbrella: high-speed rail (HSR) and magnetic levitation (maglev).” Since the term high-speed rail has by other authors been used to describe both high-speed rail and maglev, this thesis will use the terms ‘wheel-on-rail high-speed rail’ and ‘high-speed maglev’ to distinguish both technologies more precisely. As opposed to terminology, many different authors agree that HSGT systems are by far the most efficient means for transporting large passenger volumes with high speed, reliability, passenger comfort, and safety (Vuchic & Casello, 2002, p. 34) (Liu & Deng, 2004, p. 19). Accordingly, they can be considered one of the most promising solutions to provide improved intercity passenger transportation in the United States. Because both systems – wheel-on-rail high-speed rail ad high-speed maglev – run on electricity, they also do not rely on foreign oil imports (Rosenthal, 2010) and are thereby a means to achieve a higher degree of energy independence. In many aspects, the two systems are, however, very different (Liu & Deng, 2004, p. 19) which calls for a detailed evaluation of, and comparison between, the two systems.

1.2.1. Wheel-on-Rail High-Speed System

Wheel-on-rail high-speed rail uses the same mechanical principles as the first railways that emerged in England in the beginning of the 19th century as well as the first transcontinental railroad that connected the Atlantic and Pacific coasts of the United States in 1869. Support, guidance, propulsion, and braking are all achieved through the transmission of forces between steel wheels and steel rails. The more complicated part of the definition is what makes a conventional railroad a high-speed rail system. According to Guirao (2005, p. 109), “the term ‘high-speed rail’ is traditionally applied to all rail vehicles running at speeds of between 200 and 300 km/h (between 124 and 186 mph). The term ‘very high-speed rail’ is reserved for trains running at more than 300 km/h (186 mph).” Directives of the European Union on the interoperability of the Trans-European high-speed rail system define rail with speeds of less than 200 km/h (124 mph) as ‘conventional railways’; with speeds between 200 and 250 km/h (between 124 and 155 mph) as ‘upgraded conventional lines’; and with speeds of more than 250 km/h (186 mph) as ‘high-speed lines’ (Guirao, 2005, p. 109). Setting the threshold a bit lower, Vuchic and Casello (2002, p. 36) define high-speed rail “as rail system providing regular services at speeds exceeding 200 km/h (124 mph)”. Liu and Deng (2004, p. 19) add that “high-speed rail represents advanced wheel-on-rail passenger systems generally on new, dedicated rights-of-way.” Consistent with the above, they also say that “these trains currently operate in regular revenue service at maximum speeds of about 300 km/h (186 mph)”.

In the United States, definitions of high-speed rail tend to depart from what seems to be accepted international standards. The 2008 Passenger Rail Investment and Improvement Act (PRIIA) defined high-speed rail as "at least 110 miles per hour", a much lower speed than in countries with more advanced networks (Dutton, 2010). The Federal Railroad Administration (FRA) distinguishes between "conventional passenger rail (operating at speeds up to 79 miles per hour), high*er*-speed passenger rail (operating at speeds up to 150 miles per hour), and high-speed rail services (operating at speeds of 150 miles per hour or more) (GOA, 2010b)." In the FRA's 'Vision for High-Speed Rail in America' (USDOT, 2009) the speed range from 110 miles per hour through 150 miles per hour is called 'high-speed rail-regional' while true high-speed rail that exceed 150 miles per hours is called 'high-speed rail-express'.

This thesis follows the internationally most common definitions concerning 'high-speed rail'. Thus, a wheel-on-rail high-speed system is a passenger rail system that is designed to reach maximum travel speeds in commercial operation of around 300 km/h (186 mph) and whose propulsion, guidance, ad support system is based on wheel-rail interaction. Only those kinds of rail systems that fulfill this definition are examines in this thesis, because "one of the goals in building high-speed rail systems has been to increase the domain in which railway is the superior mode not only in convenience but also in speed or travel time (Vuchic & Casello, 2002, p. 34)." These wheel-on-rail high-speed systems are compared to the Transrapid high-speed maglev system.

1.2.2. High-Speed Maglev

The second high-speed ground transportation system examined in this thesis is high-speed magnetic levitation (maglev). Today, there are two high-speed maglev systems operational. The Japanese MLX01 maglev utilizes superconductivity and a guideway design that is based on repulsive magnetic forces (Vuchic & Casello, 2002, p.

40). This system holds the world speed record for ‘railed’ vehicles (581 km/h – 362 mph) and is a promising technology. However, its guideway design is very different from that of wheel-on-rail systems and its costs are not comparable to today’s wheel-on-rail high-speed systems (cf. section 3.3.1 “Investment Costs”).

The German Transrapid maglev system has already been in commercial operation in Shanghai for more than eight years. In terms of its alignment characteristics and costs, it is more comparable with wheel-on-rail high-speed systems so that it is reasonable to consider its application for the same travel markets in which wheel-on-rail high-speed systems are feasible. The Transrapid maglev system will be compared to the wheel-on-rail high-speed system in this thesis.

The Transrapid maglev system is based on attracting magnetic forces that act between the undercarriage of the vehicle that wraps around the guideway and the magnets located in the guideway. These magnetic forces pull the vehicle up to the guideway and thus make the train hover. Magnetic forces are also used for guidance, propulsion, and braking of the maglev train. This is why the Transrapid maglev does not need any wheels, axles, transmission, and overhead wires. Mechanical parts of the wheel-on-rail high-speed system are replaced by non-contact, electromagnetic systems. The functional principle of the Transrapid’s noncontact propulsion and braking can be compared to that of a rotating electric motor whose stator (the stationary part of the electric motor) is cut open and stretched along both sides of the guideway. Instead of a rotary magnetic field, the motor generates an electromagnetic traveling field. The support magnets in the vehicle serve as the rotor of the electric motor. The whole propulsion system of the Transrapid maglev is called a ‘synchronous longstator linear motor’. Contrary to wheel-on-rail high-speed, the primary propulsion component of the Transrapid maglev system (i.e. the stator packs) are not installed in the vehicle, but in the guideway. By supplying alternating current to the stator packs, an electromagnetic traveling field is generated that moves the vehicle, pulled along by the vehicle-mounted support magnets, which act as the excitation component of the longstator. Train speeds can be regulated from standstill to a maximum operating speed by varying the frequency of the alternating current. If the force direction of the traveling field is reversed, the motor becomes a generator that brakes the vehicle and feeds energy back into the network.

The operation of the Transrapid maglev system is largely automated. Conventional tasks of the train driver like controlling speeds and braking are completely replaced by the Transrapid operation control system. (Transrapid International, 2006, pp. 4-5, 13) (Blank, Engel, Hellinger, Hoke, & Nothhaft, 2004, p. 65). Due to its fundamentally different support, guidance, and propulsion technology, the Transrapid maglev has been called by its designers the "first fundamental innovation in railway technology since the construction of the first railroad (Transrapid International, 2006, p. 2)."

1.3. Recent Developments and Current Issues

As mentioned above, only two states of the 23 states (and the District of Columbia) that received funds from the ARRA are pursuing 'true high-speed rail' projects. More than half of the ARRA funds go to projects that are classified as 'conventional rail'. Still, the terminology in public discussion used to address the whole $8 billion from the ARRA funds is 'high-speed rail'. As Guirao (2005, p. 109) points out, the classification of railway services "as either conventional or high-speed [is usually done] in the full awareness of the direct association that the customer unavoidably makes between service quality and the epithet 'high speed' in the description of trains." Hence, agencies tend to refer to their project as 'high-speed rail' in order to promote and market their projects even though these projects fall into speed ranges that have standard definitions as 'conventional rail' or at most 'high*er*-speed rail'. As pointed out before, a main objective of high-speed rail systems is to increase the domain in which rail is a competitive mode in speed or travel time (Vuchic & Casello, 2002, p. 34). As such, it is important that the term ‘high-speed rail’ only be used for rail systems that fulfill these speed and travel time requirement. Due to the high number of conventional rail projects contained within the $8 billion of ARRA-funded projects, it has been criticized that “most of the money [from ARRA] will be spent more mundanely on projects to speed up conventional rail. […] There are concerns that by spreading the funds to so many different projects in so many different states, it won't be possible to make a real difference in any one place (Rosenthal, 2010).” As such, there is a risk that the benefits, which the term ‘high-speed rail’ stands for, will not be recognized by the general public when many systems that are said to be ‘high-speed rail’ are in fact ‘conventional rail’ projects that fail to offer the characteristic travel time advantages that ‘high-speed rail’ offers.

Therefore, form a public policy perspective, some number of (true) high-speed rail projects should be selected for funding, which offer good chances to show citizens the benefits of high-speed rail on a successfully-operating system. Instead, the federal government spread the money to many different regions in awarding the $8 billion in ARRA funding. In the short run, it might be beneficial to promote improvements and upgrades to existing infrastructure with the term ‘high-speed rail’. In the long run, however, one will face problems when trying to implement expensive, true high-speed rail lines when the term ‘high-speed rail’ is already associated with lower-speed speed projects that fail to justify the allocation of high amounts of funding. Rather than trying to improve the rail system at various locations simultaneously, it would, in the long run, be more effective to implement one or a few big, (true) high-speed rail projects in an optimally suited region. Such projects would serve to demonstrate the capabilities and benefits of high-speed ground transportation and set a solid foundation for the implementation of further high-speed ground transportation projects in the country. The two (true) high-speed rail projects included in the ARRA funding (i.e. California and Florida) perfectly serve this purpose. The Florida high-speed rail project can be considered a smart choice to show the benefits of high-speed rail since it will be implemented in a region (i.e. between Tampa and Orlando) that is strongly visited by people from the whole nation. So, a high number of Americans will get a chance to experience the benefits of high-speed rail.

Transportation Secretary Ray LaHood said about high-speed rail: “This is the president's vision, this is the vice president's vision, this is America's vision (Rosenthal, 2010)." However, the infusion of $8 billion in ARRA funds is only a first step in developing viable high-speed projects (GOA, 2010a, p. 5). Still, it provides a step towards a different future for intercity passenger transportation. Both high-speed ground transportation systems – wheel-on-rail high-speed rail and high-speed maglev – have the potential to revolutionize the American transportation system. The following chapter explains how the two HSGT systems will be evaluated and compared in this thesis.

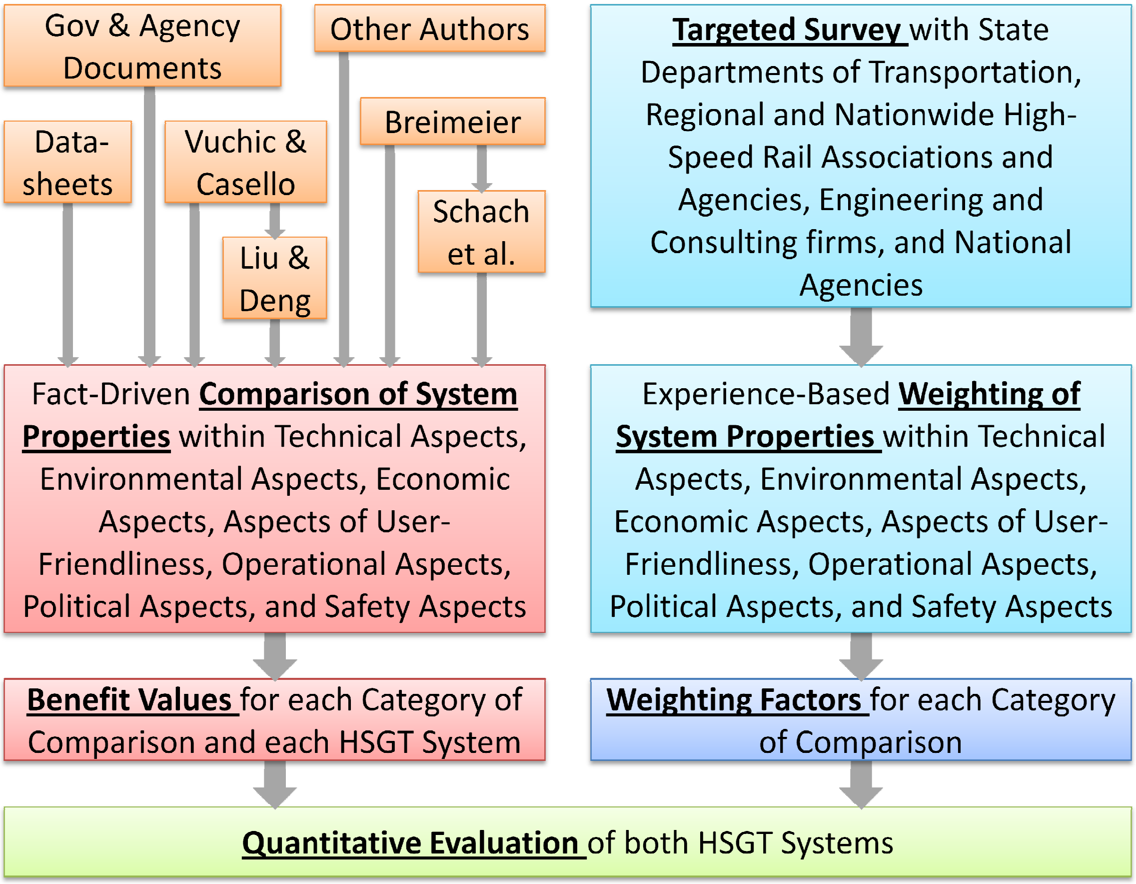
CHAPTER 2

EVALUATION METHODOLOGY

This thesis develops an evaluation methodology for comparing wheel-on-rail high-speed systems and high-speed maglev systems. As shown in Figure 1, this evaluation methodology consists of two main parts. The first part of the evaluation (cf. chapter 0 “Systems Comparison”) is a holistic comparison of both HSGT systems, which relies on different works by a variety of authors. Both high-speed ground transportation systems are evaluated based on 58 characteristics organized into 7 categories associated with technology, environmental impacts, economic considerations, user-friendliness, operations, political factors, and safety. For each of the 58 characteristics, benefit values are assigned for each system based on their performance.

These benefit values are the foundation for the second part of the evaluation (cf. chapter 0 “Quantitative Evaluation”) that develops weighting factors for each of the 58 characteristics. The assignment of these weighting factors is based on a survey that has been conducted with a variety of organizations concerned with high-speed rail, including departments of transportation, regional and nationwide high-speed rail associations and agencies, engineering and consulting firms, and national agencies. Using a multi-criteria decision making (MCDM) approach, the weighting factors are then combined with the benefit values from chapter 3. This procedure calculated utility values for the wheel-on-rail high-speed system and the high-speed maglev system for the 7 categories compared (i.e. technology, environmental impacts, economic considerations, user-friendliness, operations, political factors, and safety) as well as for both high-speed ground transportation systems as a whole.

Figure 1: Evaluation Methodology



The technical evaluation (cf. chapter 3 “Systems Comparison”) is based on the works of other researchers. One of the first American papers that contrasted wheel-on-rail high-speed rail and high-speed maglev was published in 2002 by Vuchic and Casello (An Evaluation of Maglev Technology and Its Comparison With High Speed Rail, 2002). This paper raises important questions that need to be asked about the advantages of one HSGT system over the other. It also gives good information on the most important points of comparison. However, this paper is overly critical of the maglev system. Regarding some physical facts, which were not easy to determine at the time of the article’s publication, the authors use assumptions which tend to disfavor the maglev system. This is why Liu and Deng (Liu & Deng, 2004, pp. 20-21) say that Vuchic’s and Casello’s “work has been masked by a clear bias toward [wheel-on-rail] high-speed rail and disfavor toward maglev. It also mixed the technological readiness and market values of each technology; therefore the value of the article has been heavily discounted.” The authors (Vuchic & Casello, 2002, pp. 46-47) even accuse a Federal Railroad Administration (FRA) report (USDOT, 1997) of being “politically mandated to justify maglev as a ‘solution’ [so that] the report deceptively compare[d] the speeds of the two technologies.” This dissent against the FRA’s report is mainly based on the accusation that FRA used wrong assumptions in terms of speed. However, the speeds used in the FRA report (200 mph for wheel-on-rail high-speed rail and 300 mph for high-speed maglev) coincide well with the speeds applied in reality today. The assumed maximum travel speeds in this thesis depart by only seven percent from those used in the FRA report. Still, some important questions raised by Vuchic and Casello’s have been incorporated into this thesis. Similarly, important facts about transportation systems in general, which the article focuses on, are taken into account in the present thesis.

A more holistic work titled “Transrapid or Railroad: A Technical and Economic Comparison” (Breimeier, 2002) was published in 2002. As the title suggests, the author focused on the most important technical characteristics as well as economic parameters. Most sections of this work have the same structure. The advantages of the high-speed maglev system are mentioned in the introductory sentences, before the author then elaborate on the associated disadvantages. The underlying assumptions also tend to favor the wheel-on-rail system, which is why other authors argued that Breimeier should be seen as having an anti-maglev bias (Schach, Jehle, & Naumann, 2006). This thesis incorporates all points of comparison included in Breimeier’s work and, comparing his results with those of other authors, aims to come to more neutral conclusions.

The work of Liu and Deng (Liu & Deng, 2004), published in 2004 in the Transportation Research Record, examined the Transrapid high-speed maglev system in the Beijing-Shanghai corridor in China. While the study appears to be generally neutral, some values (i.e. travel times for a certain alignment) that are more strongly based upon estimations rather than technical facts, tend to be too optimistic for the Transrapid maglev system. Unfortunately, this study does (maybe due to a language barrier) not incorporate Breimeier's work even though it had been published by this time.

By far the most thorough work comparing the Transrapid high-speed maglev system and the wheel-on-rail high-speed system is a book by Schach, Jehle, and Naumann (Schach, Jehle, & Naumann, 2006). It incorporates Breimeier's work and evaluates his assumptions and conclusions. While this book does not lean towards one system as strong as Breimeier's work, a tendency to favor the Transrapid maglev system is still discernible. Next to its thoroughness, one of the strengths of this work is the fact that almost all underlying assumptions are clearly laid out so that they could be checked and further calculations based on them. As such, the book by Schach, Jehle, and Naumann is the most important source for this thesis. In their conclusion, the authors propose a multi-criteria comparison between wheel-on-rail high-speed systems and high-speed maglev systems based on the principle of value benefit analysis. They, however, intentionally do not weight the different criteria of comparison because of the unavoidable involvement of subjectivity (Schach & Naumann, 2007, p. 143).

This thesis incorporates a weighting of all different points of comparison between the two high-speed ground transportation systems. To decrease the level of subjectivity as much as possible, the assignment of weighting factors was based on a survey, conducted with a variety of organizations that are concerned with high-speed rail.

Additional sources for this thesis included articles that focused on benefits of the maglev systems as well as a variety of other papers that talked about the benefits of high-speed rail or high-speed ground transportation in a more general sense (Thornton, 2009) (Givoni & Banister, 2007) (Guirao, 2005) (López-Pita, Teixeira, Casas, Ubalde, & Robusté, 2007) (López-Pita, Teixeira, Casas, Bachiller, & Ferreira, 2008) (Smith, 2003). Other studies (Chen, Tang, Huang, & Wang, 2007) (Witt & Herzberg, 2004) as well as manufacturer data sheets provided input for individual points of comparison and additional important individual facts and figures.

A number of agency and government documents (The United States Conference of Mayors, 2010) (USDOT, 2009) have been reviewed for this thesis. These works in particular deal with the specific needs, issues, and problems relating to the implementation of high-speed ground transportation systems in the United Stated. Many systems characteristics (e.g. clearances, right-of-way ownership, etc.) as well as regulations differ significantly from those in countries where high-speed ground transportation systems are more advanced. One particularly important issue that is being addressed in almost every case is the use of existing rail tracks. Doing so would offer the potential to save large amounts of money, but, on the other hand, limit the performance characteristics of high-speed rail systems significantly. The section about the ‘ability to use existing railroad infrastructure’ is one of the most extensive of this thesis and its analysis exceeds the evaluation of the other characteristics.

As explained above, chapter 3 “Systems Comparison” determines the benefit values for each characteristic compared between the two high-speed ground transportation systems. In this context, it is important to mention that this thesis does not claim to incorporate the level of detail of an engineering study for a particular corridor. Values for the various criteria, be it acceleration characteristics, construction costs, or travel times, are stated, summarized, evaluated, and compared. This is done to give the reader a thorough overview and to establish a solid foundation for the assignment of benefit values for each characteristic presented in chapter 3.

Obviously, not all criteria are of an equal level of importance. In order to determine the corresponding weighting factors (i.e. factors of relative importance) for each characteristic compared, a survey was conducted with 46 organizations including state departments of transportation, regional and nationwide high-speed rail associations and agencies, engineering and consulting firms, and national agencies. The survey participants were asked to assign values of importance from “0” (unimportant) through “6” (extraordinarily important) to each point of comparison. A Multi-criteria Decision Making (MCDM) approach (Yoon & Hwang, 1995) was then applied that combined the benefit values and weighting factors for each criterion, which leads to the calculation of utility values for the seven categories compared (i.e. technology, environmental impacts, economic considerations, user-friendliness, operations, political factors, and safety).

Because a high number of the system properties will vary with different speeds, the maglev train appears twice in this evaluation. For the first step of the evaluation, the maglev train is considered to travel with the same maximum speed as the wheel-on-rail high-speed train, i.e. at 300 km/h (186 mph). For the second step, both train systems are considered to travel with their own technically feasible maximum speed, i.e. the wheel-on-rail high-speed train travels with a maximum speed of 300 km/h (186 mph) while the high-speed maglev train travels with a maximum speed of 450 km/h (280 mph). The main reason for this twofold comparison is the fact that a large amount of the system characteristics change when travel speeds are modified. In order to address these changes sufficiently and, at the same time, trying to keep the evaluation procedure as simple as possible, this two-part maglev definition was used. Accordingly the ‘three’ systems that appear for each criterion are ‘wheel-on-rail high-speed rail’ travelling with a maximum speeds of 300 km/h (186 mph); ‘high-speed maglev travelling with a maximum speeds of 300 km/h (186 mph)’; and ‘high-speed maglev travelling with a maximum speeds of 450 km/h (280 mph)’.

Only benefit values are assigned (an analysis that incorporates both benefit and cost values would also have been applicable). Basically the only difference between benefit values and cost values is the direction of the scale. So, for example, the system that performs better in noise emissions could either get a low cost value or a high benefit value for this criterion. Using only one type of value assignments makes the following steps of calculation easier. The scale of assignable benefit values ranges from “1” (poor performance = minimum benefit value) through “5” (very good performance = maximum benefit value) for each individual characteristic. A scale of five possible values was chosen to offer as many values as necessary to distinguish sufficiently among the different properties and, at the same time, limit the number of possible values. Benefit values and weighting factors were then normalized. Chapter 4 “Quantitative Evaluation” explains in more detail how the normalization was undertaken.

CHAPTER 3

SYSTEMS COMPARISON

This chapter presents a systems comparison of the two high-speed ground transportation (HSGT) systems included in this thesis: wheel-on-rail high-speed rail and high-speed maglev. The chapter draws extensively on a variety of studies by other researchers.

3.1. Technical Aspects

3.1.1. Acceleration

Besides top speeds, the acceleration is one of the main determinants for travel times (cf. section 3.4.1 “Travel Time”) on a given route segment. Especially for shorter distances, it is decisive how fast a train can reach its top speed. For wheel-on-rail high-speed trains the acceleration is limited due to the low friction coefficient between the steel wheels and the rails. The acceleration of modern multiple-unit trains (also referred to as railcar trainsets), whose propulsion forces are evenly distributed among all cars of the train, is higher than the acceleration of traditional trains where propulsion is exclusively located in one or two power cars at the end of the train. Still, the acceleration of wheel-on-rail high-speed trains is significantly lower than those of high-speed maglev trains. According to Schach, Jehle, and Naumann (2006, p. 156), for instance, the ICE 3 wheel-on-rail high-speed train needs 324 seconds to reach a speed of 300 km/h (186 mph) while the Transrapid maglev reaches the same speed after only 98 seconds. A speed of 500 km/h (311 mph) is reached after 266 seconds. These values coincide well with the acceleration that travelers experience on the first Transrapid maglev route for commercial application in Shanghai. The Shanghai Maglev accelerates with an almost constant acceleration rate until it reaches the top speed of this route of 430 km/h (267mph) after approximately three minutes (Schach, Jehle, & Naumann, 2006, p. 158) (Siemens, 2006a).

The acceleration rate that is used in commercial operation is dependent both on riding comfort and technical capabilities. With respect to riding comfort the maximum acceleration and deceleration rates used for commercial operation are approximately 1.0 m/s^2 (Liu & Deng, 2004, p. 22). With the maglev these rates of acceleration are achievable almost over the whole speed range. The rate is also independent of external conditions like weather. With the wheel-on-rail system, by contrast, acceleration rates of 1.0 m/s^2 are only achievable for very low speed ranges and only under optimal conditions. According to Raschbichler (2004, p. 15) the coefficient of friction between the wheel flange and the rail, which is decisive for the transferable propulsive forces and thereby for the achievable acceleration rate, is highly variable so that acceleration rates in commercial operation are mostly significantly lower than 1.0 m/s^2.

Table 1 compares the times needed to reach a particular speed for both high-speed systems based on the average acceleration for each speed range. The table also gives the distances that the trains travel until the desired speed is reached. All the acceleration values for the wheel-on-rail system are limited due to physical properties whereas this is only true for the maglev system from 300 km/h (186 mph) on. The acceleration values up to 300 km/h (186 mph) have been intentionally limited to a more conservative value of 0.9 m/s^2 to ensure riding comfort.

Table 1: Comparison of Acceleration Times

Transrapid Maglev				Wheel-on-Rail HSR (ICE 3)			
Speed Range	Time [s]	Distance [m]	Avg. acceleration [m/s²]	Speed Range	Time [s]	Distance [m]	Avg. acceleration [m/s²]
0 – 150 km/h	46	950	0.90	0 – 150 km/h	84	1,900	0.54
0 – 200 km/h	62	1,730	0.90	0 – 200 km/h	132	4,300	0.49
0 - 300 km/h	98	4,300	0.90	0 - 300 km/h	324	17,900	0.34
0 - 400 km/h	156	9,900	0.81	0 - 400 km/h			
0 - 500 km/h	266	23,300	0.66	0 - 500 km/h			

(Source: Schach, Jehle, and Naumann, 2006, p. 156)

Table 1 shows that the maglev system accelerates to a speed of 300 km/h (186 mph) in a few more seconds than the ICE 3 wheel-on-rail train needs to reach half that speed. The distance the maglev has traveled by then is more than twice as long as the wheel-on-rail trains distance. The maglev also reaches a speed of 500 km/h (311 mph) faster than the conventional high-speed train reaches 300 km/h (186 mph). In agreement with the values from Table 1, Liu and Deng (2004, p. 22) state that the high-speed maglev needs approximately 4 kilometers (2.5 miles) to accelerate to 300 km/h (186 mph), whereas the wheel-on-rail trains need approximately 20 kilometers (12.4 miles) to reach the same speed. Accordingly, the following benefit values for acceleration (cf. Table 2) have been assigned.

Table 2: Benefit Rating for Acceleration

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	2	5	4

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.1.2. Braking Performance

Similar to acceleration, the achievable braking performance is also an important factor for the travel time on a given route segment. The higher the achievable braking rate, the longer the train can travel at a higher speed. Furthermore, a higher maximum braking rate increases the level of safety. For the wheel-on-rail high-speed trains, the braking rate is partially dependent on external conditions like temperature and precipitation. The rate of deceleration of the maglev system, by contrast, is not dependent upon weather conditions. It is solely limited by the maximum level acceptable related to passenger comfort. (Siemens, 2006c)

Wheel-on-rail high-speed trains have up to three different braking systems. A regenerative brake converts kinetic energy into electrical energy and thereby slows down the trains and feeds energy back into the power system. A mechanical brake takes effect directly on the wheel-rail interaction and thus slows down the train at the expense of mechanical wear. An eddy-current brake is additionally applied when highest braking rates are necessary. Because the Transrapid maglev has a significantly lower weight than wheel-on-rail trains (cf. 3.1.5 “Train Weight”), it can reach higher braking rates with only its regenerative brake than wheel-on-rail trains can with all their braking systems being applied simultaneously. To slow down the maglev, the phase angle of the travelling magnetic field is shifted. This causes that the traction motor to become a generator. Just like the regenerative brake of wheel-on-rail high-speed trains, this slows down the maglev and feeds back its energy into the power supply system as electrical energy (Siemens, 2006c). For cases of emergency, e.g. power outages, the Transrapid maglev also possesses an eddy-current brake that enables the maglev to reach the next station or auxiliary stopping area (cf. section 3.7.8 “Evacuation of Trains”).

Based on these physical properties, Table 3 compares the values of braking distances and times needed to reach a complete stop from a given travel speed. The braking distance of the Transrapid maglev from a speed of 300 km/h (186 mph) to a complete stop is just over half as long as the distance the wheel-on-rail ICE 3 needs from the same speed. From a speed of 400 km/h (249 mph) the maglev has a slightly lower braking distance than the wheel-on-rail train from a speed of 300 km/h (186 mph).

Table 3: Comparison of Braking Distances and Times until Complete Stop

Transrapid Maglev				Wheel-on-Rail HSR (ICE 3)			
Speed Range	Time [s]	Distance [m]	Avg. acceleration [m/s²]	Speed Range	Time [s]	Distance [m]	Avg. acceleration [m/s²]
150 - 0 km/h	44	930	0.96	150 - 0 km/h	84	1,700	0.48
200 - 0 km/h	58	1,576	0.94	200 - 0 km/h	108	3,100	0.53
300 - 0 km/h	87	3,600	0.95	300 - 0 km/h	168	6,900	0.49
400 - 0 km/h	117	6,725	0.98	400 - 0 km/h			
500 - 0 km/h	147	10,475	0.97	500 - 0 km/h			

(Source: Schach, Jehle, and Naumann, 2006, p. 156)

In sum, Transrapid maglev trains can achieve twice as high braking rates as wheel-on-rail high-speed trains, taking into account both physical and comfort-related limitations. The absolute braking distance from a speed of 300 km/h (186 mph) to a complete stop is a bit more than half as long as for maglev trains than for wheel-on-rail high-speed trains. From a speed of 450 km/h (280 mph) the braking distance of a maglev train is somewhat longer than that for the wheel-on-rail system from 300 km/h (186 mph). Given these considerations, the following benefit values in terms of braking performance (cf. Table 4) have been assigned to the two high-speed systems.

Table 4: Benefit Rating for Braking Performance

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	3	5	4

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.1.3. Travel Speed

Travel time is one of the most important determinants for passengers in choosing one mode over another. Travel time strongly depends on the average travel speed, which is dependent on maximum speed, acceleration, braking rate and dwell times at stations. While the latter three are dealt with in other sections (cf. section 3.1.1 "acceleration", section 3.1.2 "braking rate", and section 3.5.3 "stopping time at stations"), this section focuses on maximum speeds.

Today, the fastest scheduled rail connection in Europe is the Spanish AVE wheel-on-rail high-speed train that runs between Madrid and Barcelona. For this 640-kilometer (398 miles) line the train needs less than two and a half hours (Siemens, 2006a). This means an average travel speed of more than 250 km/h (155 mph). According to Liu and Deng (2004, p. 22), the maximum operation speeds of the French TGV, the Japanese Shinkansen, and the German ICE wheel-on-rail trains are 300 km/h (186 mph). The suggested maximum operating speed of the Transrapid maglev is 450 km/h (280 mph). Design speeds for track alignment are sometimes a bit higher in order to be prepared for possible future speed upgrades. The highest design speeds for the wheel-on-rail system are 350 km/h (218 mph) (French TGV and Spanish AVE), whereas the design speed of maglev can be up to 550 km/h (342 mph).

Schach, Jehle, and Naumann (2006, p. 153) add that in the future maximum speeds for wheel-on-rail trains in commercial operation will be not significantly higher than 300 km/h (186 mph). Liu and Deng (2004, p. 22) agree that the practical limits of wheel-on-rail HSR is around 300 km/h (186 mph) due to the increasing driving resistance and mechanical wear with increasing speeds. While today “three different manufacturers can provide [wheel-on-rail] trains designed to operate at 350-360 km/h (218-224 mph)” (Thornton, 2009, p. 1902) “technical problems have prevented significant commercial operation over 320 km/h (199 mph) (Thornton, 2009, p. 1916).”

For the maglev system, on the contrary, speeds in excess of 550 km/h (342 mph) are well within the technological limits (Liu & Deng, 2004, p. 22). Therefore, the Transrapid maglev is assigned a higher benefit rating in this category (cf. Table 5). For the case that maglev is intentionally operated at the same speed as wheel-on-rail HSR (in order to improve other parameters at the expense of speed, cf. chapter 0 “Methodology”) the Transrapid is assigned the same rating as wheel-on-rail high-speed rail.

Table 5: Benefit Rating for Travel Speed

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	3	3	5

1 = Minimum Benefit Value;   5 = Maximum Benefit Value

3.1.4. Wear and Degradation

Due to the physical contact between the wheel and the rail, wheel-on-rail trains are subject to wear (López-Pita, Teixeira, Casas, Bachiller, & Ferreira, 2008). The most common models to determine wear are dependent on speed. For non-high-speed railroads there are empirical formulae that describe wear dependent on speeds. These results, however, cannot directly be transferred to high-speed trains. Gers, Hübner, Otto, and Stiller (1997, p. 6) estimate that high-speed rails have, on average, to be replaced after 25 years. Breimeier (2002, p. 23) specifies the average durability as 20 years. However, the new high-speed track between Cologne and Frankfurt in Germany, which is operated with a maximum speed of 300 km/h (186 mph), has been reported to need rail replacement only after five to seven years[1].

A 2007 study conducted by López-Pita, Teixeira, Casas, Ubalde, & Robusté (Evolution of track geometric quality in high-speed lines: Ten years experience of the Madrid–Seville line, 2007), which was based on maintenance data on the Madrid-Seville high-speed line in Spain, focused on the wear and degradation on the track. Based on data from 10 years, the study found that track sections where the track deteriorates most rapidly correspond to segments of the line running over short rigid structures like culverts and the beginnings of the transition between bridges and embankments. Track sections located on bridges also showed higher deterioration rates. Since the evaluated high-speed lines have not been in operation for long enough, no estimations about the total lifetime of the rails were made. Still, the study has shown once again that wear and tear is a major issue on wheel-on-rail high-speed rails that can only be mitigated but never totally remedied. The high circumferential wheel speeds produce micro skid results at the wheel base point of the vehicle, which can reduce the transferable tractive force (Raschbichler, 2004, p. 15). Also so-called head cracks reduce comfort as their existence increases the degradation rate. This is why rails have to be grinded regularly (Schach, Jehle, & Naumann, 2006, p. 137).

One major advantage (and main characteristic) of maglev systems is their lack of any physical contact between guideway and vehicle during their operation. Electronic and electromagnetic components, which are essentially wear-free, are used in place of mechanical components that wear quickly (Siemens, 2006b, p. 11). Because no part of the vehicle touches the guideway, mechanical deterioration is simply non-existent in maglev systems. This is why none of these parts will ever have to be replaced due to

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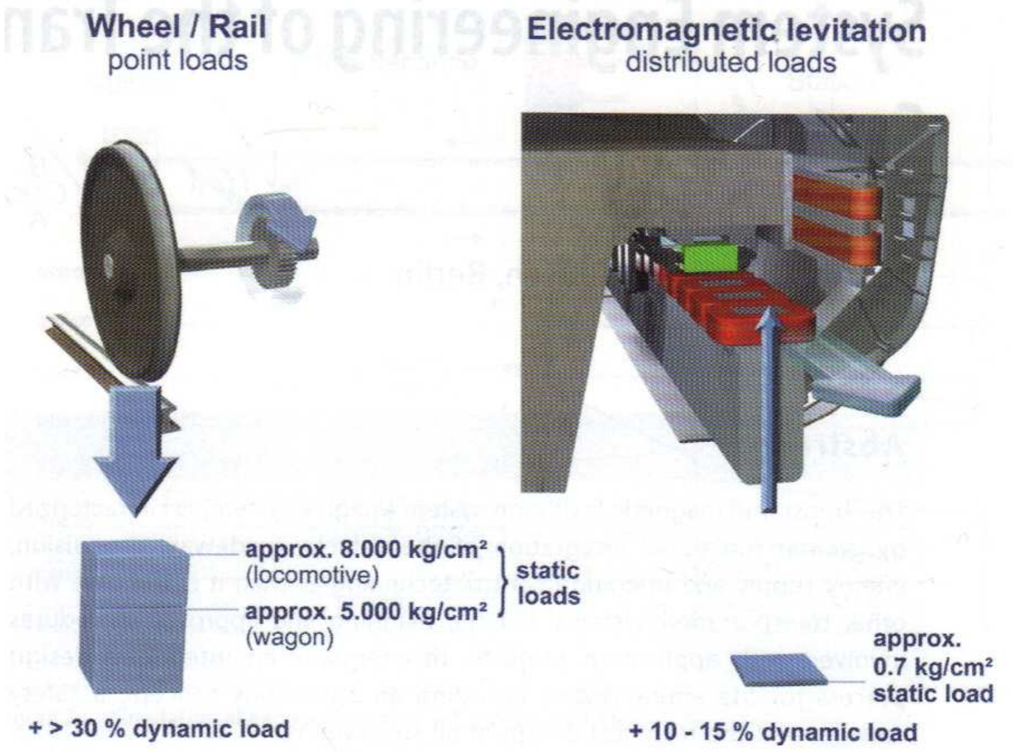
[1] http://www.wdr.de/themen/verkehr/schiene02/bahn/trasse_koeln_frankfurt/index.jhtml. Accessed April 26, 2010

mechanical wear. Figure 2 shows the stresses each of the two high-speed ground transportation system puts on their respective guideway. Due to the very small area through which wheel-on-rail trains transmit their load to the rails, the point stresses on the rail are very high. They range between 5000 and 8000 kg/cm² (500 and 800 N/mm²) in static load. Instead of point stresses, the Transrapid maglev only transmits plane loads through its support magnets to its guideway that are significantly lower with approximately 0.7 kg/cm² (0.07 N/mm²).

Figure 2: Comparison of Loads Transmitted to the Guideway



(Source: Raschbichler, 2006, p. 15)

For its low loads on its guideway and its non-contact propulsion, maglev systems have been called zero-maintenance systems. While this statement is obviously true for mechanical parts, it is still an exaggeration. Breimeier (2002, p. 23), for instance, raises the concern that the maglev’s guideway might, even in the absence of physical contact, still be subjected to wear due to variation in traffic, corrosion and other impacts. He also suspects that parts of the propulsion system and electronics might still need maintenance or replacement for other reasons than mechanical wear. He also points out that the exchange of wheels and rails of the wheel-on-rail high-speed system has become a routine task so that associated costs are limited. On the other hand, maintenance and replacement of elements of the maglev system could be expensive when sophisticated electronics or the magnets of the propulsion system are involved. So, he raises the question of whether the substitution of inexpensive wearing parts on the wheel-on-rail high-speed system as compared to sophisticated electronic parts on the maglev system is economical.

Moreover, some engineers are concerned that the levitation gap of only 10 millimeters (0.4 inches) between the maglev’s support magnets and the longstator of the guideway may create challenges due to potential settling of the guideway. The variation of the gap should be controlled to less than one millimeter (0.04 inches) which might require significant engineering inspection (Liu & Deng, 2004, p. 26) that could be seen to somewhat outweigh the saved maintenance effort. The same concern, however, can be true for modern non-ballasted track substructures that are similarly sensitive to settling and therefore require thorough inspections.

For both high-speed ground transportation systems, it is true that with increasing speeds higher forces have to be transmitted between the vehicle and its guideway. Only on the wheel-on-rail system, however, can increased speeds cause increased wear and tear. On the high-speed maglev systems any potential degradation is independent of speed. While maintenance costs are addressed in section 3.3.2 “Maintenance, Repair, and Rehabilitation Costs”, this section focuses on the physical properties causing wear and tear. Following the above considerations, it is obvious that the material requirements and the number of replacement parts are significantly higher for wheel-on-rail high-speed rail.

Since not all of the questions raised above could be answered with confidence, the benefit rating for maglev (cf. Table 6) must be tempered with caution.

Table 6: Benefit Rating for Wear and Degradation

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	2	4	4

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.1.5. Train Weight

In general, a lower train weight is favorable as it helps to lower construction costs, wear, and material consumption. Table 7 lists the weights and per-passenger weights of different wheel-on-rail high-speed trains and the Transrapid high-speed maglev.

Table 7: Weights of the Transrapid Maglev and different Wheel-on-Rail High-Speed Trains

	Transrapid Maglev[2]	ICE 3[3]	TGV POS[4]	Shinkansen N700-I[5]	Velaro RUS[6]	Velaro CN[7]
Passenger Capacity	438	415	380	636	604	601
Weight	247.3 t	409 t	427 t	365 t	651 t	447 t
Weight per Passenger	0.56 t	0.99 t	1.12 t	0.57 t	0.92 t	0.74 t

Table 7 shows that the Transrapid maglev has a significantly lower per-passenger weight than all the wheel-on-rail high-speed trains except the Japanese Shinkansen that

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[2] Schach and Naumann, 2007, p. 142

[3] Ibid.

[4] http://www.hochgeschwindigkeitszuege.com/france/index_tgv_est.htm Accessed June 1st, 2010

[5] http://www.japantransport.com/seminar/JRCENTRAL.pdf Accessed July 12, 2010

[6] http://www.siemens.com/pool/en/whats_new/features/moscow_to_st_petersburg/velaro_rus.pdf Accessed July 22, 2010

[7] http://www.siemens.com/press/pool/de/materials/industry/imo/velaro_cn_en.pdf Accessed July 22, 2010

shows almost the exact same value as the Transrapid maglev. One important factor for maglev's lower weight is that, unlike the traditional wheel-on-rail systems, the propulsion system of the Transrapid high-speed maglev is not mounted on board of the vehicle, but in the guideway (Siemens, 2006b, p. 21). This reduces the weight significantly. The second most important parameter influencing the per-passenger weight is connected to the compactness of the train that is dealt with in the following section (section 3.1.6 "Compactness of Train). While the ICE and the TGV are 2.95 meters (9.7 feet) wide, the Transrapid maglev measures 3.70 meters (12.1 feet). So, the maglev can seat more passengers on a given train length, which reduces the per-passenger weight. The width of Japanese Shinkansen wheel-on-rail bullet train of 3.36 meters (11.0 feet) ranges well between the ICE and TGV wheel-on-rail high-speed trains and the Transrapid maglev. This is one reason why the Shinkansen also shows a lower per-passenger weight. Also, the Shinkansen has a slightly lower seating width and a much lower share of first-class seating than its European counterparts which helps to further reduce the per-passenger weight. All these properties combined make the Shinkansen wheel-on-rail high-speed train show the almost same value for per-passenger weight as the Transrapid maglev (cf. Table 7).

While the Transrapid maglev is 3.70 meters (12.1 feet) wide, both the German ICE and the French TGV wheel-on-rail high-speed trains are about 2.95 meters (9.7 feet) wide because clearance envelopes do not allow for a wider vehicle body. These envelopes, however, do not apply for the United States. Freight cars in the U.S., for example, are allowed a width of 10 feet and 10 inches (10.83 feet). Only if they exceed this width are they considered "excess width" cars and further regulations apply. The 10 feet and 10 inches equals 3.302 meters, which is almost the width of the 3.36-meter-wide (11.0 feet) cars of the Japanese Shinkansen. The new Chinese Velaro CN and Russian Velaro RUS wheel-on-rail high-speed trains, which were developed based on the 2.95-meter-wide (9.7 feet) Spanish Velaro E (AVE) and German ICE 3 trains, also show a widened car body of 3.265 meters (10.7 feet). As can be drawn from Table 7, the Velaro CN and Velaro RUS trains therefore also have lower weight-per-passenger values. Due to the wider clearance envelopes on existing railroad lines in the Unites States and the freedom in defining clearance envelopes for completely new constructed high-speed tracks, it can be assumed that such wider vehicles will be used on future U.S. high-speed lines. A fair comparison, however, has to assume the same seating comfort (cf. section 3.4.3 "Comfort") so that a realistic value for the per-passenger value of a wheel-on-rail high-speed train operating in the United States will range around a value of the 0.8 tons per passenger (maglev: 0.56 tons per passenger). Therefore, Table 8 shows the following benefit rating.

Table 8: Benefit Rating for Train Weight

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	3	5	5

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.1.6. Compactness of Train

The term compactness describes the external measures of a car related to its internal space. A short vehicle that offers the same floor space as a longer vehicle can thus be considered more compact. A more compact vehicle is in general superior in aerodynamic performance and more economical in some respects of infrastructure. For example, platform lengths can be shorter to allow for the same transportation capacity, which means that stations in general can be smaller if more compact vehicles are used.

Even between different wheel-on-rail high-speed trains, there are differences in terms of compactness. Multiple-unit trains, whose driving force is equally distributed among all cars of a train instead of having the driving force concentrated in one or two locomotives at the ends of the train, generally have a better seats-to-length ratio. This is because "the full length of the multiple-unit train is available for seating, catering and luggage storage. In other words, the space available to passengers [is] increased by 20 percent from the same length of train."(Siemens, 2006a) This is true for the German ICE 3 and Japanese Shinkansen trains. The French TGV uses locomotives that decrease its seats-to-length ratio. With the newly developed AGV (Automotrice à grande vitesse = high-speed self-propelled carriage), the manufacturer of the French TGV also entered into the multiple-unit train market.

In developing the Transrapid maglev, the engineers did not have to take into consideration the normal limitations of conventional rail systems (Siemens, 2006c). The width of the maglev vehicle could be optimized regarding a number of parameters like passenger comfort and aerodynamic drag without having to respect constraints like standard track gauge that limits the width of wheel-on-rail high-speed trains. Thus, the Transrapid maglev shows better values in term of compactness (cf. Table 9).

Table 9: Compactness of the Transrapid Maglev and different Wheel-on-Rail High-Speed Trains

	Transrapid Maglev[8]	ICE 3[9]	TGV POS[10]	Shinkansen N700-I[11]	Velaro RUS[12]	Velaro CN[13]
Passenger Capacity	438	415	380	636	604	601
Length	128.3 m	200 m	200 m	204.7 m	250.3 m	200.0 m
Compactness (Length per Passenger)	0.29 m	0.48 m	0.52 m	0.32 m	0.41 m	0.33 m

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[8] Schach and Naumann, 2007, p. 142

[9] Ibid.

[10] http://www.hochgeschwindigkeitszuege.com/france/index_tgv_est.htm Accessed June 1st, 2010

[11] http://www.japantransport.com/seminar/JRCENTRAL.pdf Accessed July 12, 2010

[12] http://www.siemens.com/pool/en/whats_new/features/moscow_to_st_petersburg/velaro_rus.pdf Accessed July 22, 2010

[13] http://www.siemens.com/press/pool/de/materials/industry/imo/velaro_cn_en.pdf Accessed July 22, 2010

As pointed out in section 3.1.5 “Train Weight”, the new Chinese Velaro CN and Russian Velaro RUS wheel-on-rail high-speed trains have comparatively wide car bodies of 3.265 meters (10.7 feet). This can allow for a 2+3-seating configuration (i.e. five seats in one seating row), instead of the 2+2-seating configuration on the ICE and TGV, which improves the trains compactness. Due to the considerations about clearance envelopes in the United States it can be assumed that wider vehicles will be used in the U.S. Accordingly, the values of compactness for wheel-on-rail high-speed trains in the U.S. will range around the values of the Velaro RUS trains. The even better compactness value of the Chinese Velaro CN train is achieved by a narrower seating arrangement, which cannot be assumed to fulfill the comfort requirements of future U.S. high-speed systems. Accordingly a length-per-passenger value of approximately 0.4 meters (1.3 feet) for wheel-on-rail high-speed trains, compared to a value of 0.29 meters (0.95 feet) for the maglev system, leads to the following benefit rating (cf. Table 10).

Table 10: Benefit Rating for Compactness of Train

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	4	5	5

1 = Minimum Benefit Value;   5 = Maximum Benefit Value

3.1.7. Flexibility in Track Alignment

Designing a track for a high-speed ground transportation system is a complicated task that involves the consideration of a great number of interrelated parameters. The shortest way to connect two points is obviously a straight line. Because of topographical characteristics and property ownership, however, a straight-line connection is almost never achievable. In reality, track alignment is heavily constrained by topographical properties like hills, slopes, rivers, creeks, and sounds as well as protected habitats and human settlements, which force the guideway to depart from a straight alignment. The extent to which the alignment of a high-speed ground transportation system can depart from a straight line is dependent on the minimum curve radii, the maximum achievable longitudinal slope and the achievable rates of change of these two figures. All theses parameters are limited for either technical or comfort-related reasons.

The minimum possible curve radius of a guideway is determined by the centrifugal forces that the passengers experience when the train negotiates a curve. Centrifugal forces are partially dissipated through the application of a cross slope (also called cant) in curves, which deflects part of the centrifugal forces into normal forces. This decreases the lateral accelerations that the passengers experience and thereby increases ridership comfort. So, smaller radii can be chosen for a curve with a given travel speed when the cross slope is increased. The maximum cross slope, however, is limited by physical and comfort-related properties. For wheel-on-rail high-speed systems it needs to be ensured that a train can safely perform an emergency stop at any location of the track. So, cross slopes have to be limited to enable the train to negotiate a curve at a speed lower than its actual design speed without being in danger of tilting over or derailing. The Transrapid maglev system, on the contrary, is designed in a way that in an emergency a fixed emergency stop can always be reached (cf. section 3.7.8 “Evacuation of Trains”). Also, it is technically impossible for a Transrapid maglev to tilt over or to derail because the train’s undercarriage wraps around its guideway (cf. section3.7.1 “Risk of Derailment”). Therefore, cross slopes in curves of maglev tracks can be significantly higher (up to 12 degrees (Schwindt, 2004, p. 34) (Schach, Jehle, & Naumann, 2006, p. 80)) than those of wheel-on-rail high-speed trains (at most 6.9 degrees (Schach, Jehle, & Naumann, 2006)). Accordingly, maglev guideways can be designed with smaller curve radii for a given speed than tracks for the wheel-on-rail system. Corresponding values for minimum curve according to different authors are given in Table 11.

Table 11: Comparison of Minimum Radii for Horizontal Curves

Speed	Minimum Radii for Horizontal Curves for the Wheel-on-Rail High-Speed System [m] (cross slope: 6.9 degree)		Minimum Radii for Horizontal Curves for the High-Speed Maglev System [m] (cross slope: 12.0 degree)		
	Own Calculation[14]	Siemens, 2006b, p.10	Schwindt, 2004, p. 34	Schach et al., 2006, p. 81	Siemens, 2006b, p. 10
200 km/h	1,406	1,500	8,55		900
300 km/h	3,165	3,300	1,920	1,937	1,700
350 km/h	4,307			2,637	
400 km/h	-	-	3,415	3,444	
450 km/h	-	-		4,360	
500 km/h	-	-		5,382	
550 km/h	-	-	6,455		

The values by the different authors coincide quite well. The following statements are based on the values by Schach et al. since they reference the calculations of their values. For a design speed of 300 km/h (186 mph), the wheel-on-rail system requires a minimum curve radius that is approximately 63 percent greater than the minimum curve radius for the maglev system for the same design speed. For a maglev guideway with a design speed of 400 km/h (249 mph), the minimum curve radius does not have to be much greater (i.e. only approximately 9 percent) than that for a track of the wheel-on-rail system with a design speed of 300 km/h (186 mph).

The minimum curve radii on real tracks are mostly chosen greater than the theoretical minimum values from Table 11. The minimum curve radius on the Spanish high-speed line between Madrid and Seville is 4,000 meters (13,123 feet) for horizontal curves that are designed to be negotiated with 270 km/h (168 mph). The minimum curve radius on the line between Madrid and Barcelona where the projected maximum speed is

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[14] based on formula from Schach, Jehle, and Naumann, 2006, p. 73

350 km/h (218 mph) is 6,500 meters (21,325 feet) for curves that are designed to be travelled with maximum speed (Guirao, 2005, p. 111). On the Cologne-Frankfurt wheel-on-rail high-speed track, the minimum curve radius is 3,350 meters (10,991 feet; cross slope: 6.5 degree) for a design speed of 300 km/h (186 mph) (Schach, Jehle, & Naumann, 2006, p. 71).

The propulsion of wheel-on-rail trains is based on physical friction. Because the friction between a steel wheel and a rail is very limited, the acceleration, the deceleration, and the maximum longitudinal slopes that these trains can achieve, are limited. Maximum slopes can, however, be increased when multiple-unit trains are used. The propulsion force of multiple-unit trains is distributed among all cars of the train instead of being concentrated in one or two locomotives which serve as the only traction units for conventional trains. Due to the optimized distribution of driving force, a multiple-unit trains can negotiate slopes about three times as steep as the maximum slopes of conventional trains whose whole driving force is located in locomotives at the ends of the train. On Siemens’s Velaro wheel-on-rail high-speed train, for instance, half of all axles are driven, which ensures the ability to climb grades as steep as 4 percent (Siemens, 2006a) (Liu & Deng, 2004, p. 22). In general, the maximum slope of wheel-on-rail high-speed lines in Europe, which are designed for multiple-unit trains, is by legal regulations limited to 3.5 percent (Schach, Jehle, & Naumann, 2006, p. 79). As maglev trains use magnetic power instead of friction to transmit driving force, they can negotiate steeper longitudinal slopes up to 10 percent (Schach, Jehle, & Naumann, 2006, p. 82) (Schwindt, 2004, p. 34) (Liu & Deng, 2004, p. 22). Table 12 gives the minimum vertical radii for crests (hilltops) for both systems according to different authors. Table 13 gives the minimum values for vertical radii for sags (valleys).

Table 12: Comparison of Minimum Radii for Vertical Curves in Crests (Hilltops)

Speed	Minimum Radii for Vertical Curves (Crest) for the Wheel-on-Rail High-Speed System [m]		Minimum Radii for Vertical Curves (Crest) for the High-Speed Maglev System [m]		
	Schach et al., 2006, p. 80	Siemens, 2006b, p. 10	Schwindt, 2004, p. 34	Schach et al., 2006, p. 83	Siemens, 2006b, p. 10
200 km/h	15,432	16,000	5,145	5,144	4,500
250 km/h	24,113				
300 km/h	34,722		11,575	11,574	
400 km/h	-	-	20,580	20,576	
450 km/h	-	-		26,042	
500 km/h	-	-		32,150	
550 km/h	-	-	38,905		

Table 13: Comparison of Minimum Radii for Vertical Curves in Sags (Valleys)

Speed	Minimum Radii for Vertical Curves (Sag) for the Wheel-on-Rail High-Speed System [m]		Minimum Radii for Vertical Curves (Sag) for the High-Speed Maglev System [m]		
	Schach et al., 2006, p. 80	Siemens, 2006b, p. 10	Schwindt, 2004, p. 34	Schach et al., 2006, p. 83	Siemens, 2006b, p. 10
200 km/h	10,288	14,200	2,575	2,572	3,200
250 km/h	16,075				
300 km/h	23,148		5,790	5,787	
400 km/h	-	-	10,290	10,288	
450 km/h	-	-		13,021	
500 km/h	-	-		16,075	
550 km/h	-	-	19,455		

All in all, the corresponding values do not differ significantly between the different authors. It can be seen that for both crests and sags the Transrapid high-speed maglev system has significantly lower values for minimum radii. As opposed to horizontal curves for which different physical properties (i.e. maximum achievable cross slopes) determine the minimum curve radii, the radii for vertical curves are solely dependent on the maximum values of vertical acceleration. These values are hardly constrained by physical properties, but limited to ensure certain levels of comfort. The vertical acceleration on which the minimum radii for vertical curves in the above tables are based upon, differ by a factor of four. Even though this is in line with existing regulations, it has to be questioned whether it is justifiable to make passengers experience vertical accelerations four times as high in a maglev train compared to traveling in a wheel-on-rail high-speed train. That these assumptions might not hold true is considered in the assignment of benefit values.

It is still true that high-speed maglevs can handle steeper slopes than wheel-on-rail high-speed trains. So, based on smaller minimum radii and steeper maximum longitudinal slopes for a given speed, Breimeier (2002, p. 12), Liu and Deng (2004, p. 22), and Schach, Jehle, and Naumann(2006, p. 83) agree that maglev guideways can be more easily integrated into a given topography. This offers significant advantages, especially in hilly or mountainous terrain or in areas were smaller radii are required due to buildings or other infrastructure systems. For the new California high-speed rail system that is planned as a wheel-on-rail system, for instance, operating speeds had to be reduced on the track segment “from Palmdale southward toward the Los Angeles region […] resulting from physical constrains, such as track curvature typical for heavily urbanized areas (The United States Conference of Mayors, 2010, p. 10).”

The advantages of the high-speed maglev system can, however, not come into play in all alignment situations due to limitations of the rate of change in track slope. As such, it might not be possible to take advantage of the ability of a maglev train to “climb” steeper slopes when the distance necessary to convert a flat track into a certain slope would be too long (Breimeier, 2002). Concerns that “excessive guideway superelevations in curves are not acceptable for vehicles which have standing passengers” (Vuchic & Casello, 2002, p. 42) do, by contrast, not appear to be very relevant since vehicles for long-haul trips are generally not designed to accommodate standing passengers, but rather to offer every passenger a seat.

Another advantage of the high-speed maglev system is its suitability for an elevated alignment (cf. section 3.2.1 “Land Consumption”). The maglev’s undercarriage wraps around its guideway which has an appearance of a beam bridge. To form an elevated track, not much more than just adding columns is necessary. Such an elevated guideway supports a more flexible alignment since abrupt changes in the terrain can be more easily compensated by adjusting the height of the columns that support the elevated guideway. For the wheel-on-rail high-speed system this task is more complicated. Tracks for the wheel-on-rail system are, for reasons of construction costs, up to heights of 10 meters (32.8 feet) preferably designed on embankments (instead of bridges), which requires extensive earthmoving (cf. section 3.2.1 “Land Consumption”) (López-Pita, Teixeira, Casas, Ubalde, & Robusté, 2007).

An option to increase either the flexibility in alignment or travel speeds in a given alignment for the wheel-on-rail system is the use of tilting trains. Tilting trains are trains that have a mechanism enabling the train to tilt to the inside of a curve. From the passengers’ point of view, this means that the tilting mechanism (in addition to the given cross slope of the track) increases the angle against the horizontal. So, a higher share of the centrifugal forces on the passengers while traveling a curve can be deflected as normal forces. This means that the lateral acceleration the passengers experience will be lower for a given speed when the tilting mechanism is applied. For tilting trains used in Europe, speeds can be 21 percent higher for any given curve radius (Schach, Jehle, & Naumann, 2006, p. 75). More sensitive people, however, experience the tilting of the train as unpleasant. Furthermore, the tilting system only changes the tilt of the passenger compartments. The way the wheels run on the rail is not changed by the tilt system. This means, that the wheelset of the train just travels with a higher speed through the curve without respective changes in cross slope or other track design parameters. The additional forces, which are thereby applied to the wheels and rails, increase mechanical wear of these components. Moreover, it has been argued that for tilting trains speeds higher than

230 km/h (143 mph) cannot be assumed to be feasible (Schach, Jehle, & Naumann, 2006, pp. 76, 84). This is why the application of titling trains appears to be an option for existing tracks whose alignment cannot be changed rather than for new tracks for which higher design speeds are desired.

In summary, the high-speed maglev system offers more flexibility in alignment than the wheel-on-rail system. Especially for horizontal curves, minimum curve radii are lower due to physical system characteristics. Similarly, the maximum longitudinal slopes of the high-speed maglev system are (also due to physical properties) more favorable for a more flexible alignment. In terms of minimum radii for vertical curves the maglev system also performs better when compared for equal maximum travel speed (i.e. 300 km/h – 186 mph). Also, the suitability of the maglev system for an elevated guideway benefits flexibility in alignment. Therefore, the maglev system is for a given speed significantly more flexible in alignment than the wheel-on-rail high-speed system. If higher travel speeds are chosen for the maglev system, the minimum radius has to be increased and the maximum rate of change in slope has to be decreased. Summing up all relevant parameters, the flexibility in alignment of a maglev traveling at 450 km/h (280 mph) is similar to that of the wheel-on-rail system traveling at 300 km/h (186 mph). Consequently, the benefit values shown in Table 14 have been assigned.

Table 14: Benefit Rating for Flexibility in Track Alignment

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	3	5	3

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.1.8. Driving Resistance

In its brochures, the manufacturer of the Transrapid maglev advertises “the total absence of friction [as] a central feature of the Transrapid’s propulsion system

(Transrapid International, 2006).” However, the statement about the total absence of friction is true when only mechanical friction is considered. Wheel-on-rail high-speed systems are subjected to rolling resistance due to the interaction of the wheels on the rail. Since the maglev vehicle does not have any physical contact to its guideway, there indeed is no mechanical friction between the vehicle and the guideway. There is, however, a magnetization resistance which the Transrapid maglev is subjected to. According to Breimeier, the weight-specific value of this electromagnetic resistance is greater than the rolling resistance of the wheel-on-rail high-speed system. Only due to the lower vehicle weight of the maglev (cf. section 3.1.5 “Train Weight”), does the magnetization resistance force which is taking effect on the maglev vehicle become smaller than the rolling-resistance force of the wheel-on-rail system (Breimeier, 2002, pp. 19, 57). Schach, Jehle, and Naumann (2006, pp. 175-176) give very similar values for the magnetization resistance force of the maglev. Their values for the rolling resistance forces of the wheel-on-rail high-speed system are, however, a multiple higher than Breimeier’s value. They suspect that Breimeier’s values are only applicable for ideal conditions (new wheels and rail, straight alignment without curves etc.). All values are summarized in the following Table 15.

Table 15: Comparison of Rolling Resistance Forces of the Wheel-on-Rail High-Speed System and Magnetization Resistance Forces of the High-Speed Maglev System

Speed [km/h]	Rolling Resistance Forces of the Wheel-on-Rail High-Speed System [kN]		Magnetization Resistance Forces of the High-Speed Maglev System [kN]	
	Breimeier (p. 56)	Schach et al. (p. 175)	Breimeier (p. 57)	Schach et al. (p. 176)
100	5.0	10.7	4.3	3.7
150	5.9	14.1	5.5	4.6
200	6.8	18.9	6.5	5.4
250	7.7	25.0	7.3	6.1
300	8.7	32.5	8.1	6.8
350	9.6	41.4	8.9	7.4
400	-	-	9.6	8.0
450	-	-	10.2	8.5

From a speed of 100 km/h (62 mph) or more, aerodynamic drag is the most important component of resistance (Schach, Jehle, & Naumann, 2006, p. 177). Aerodynamic drag is mainly dependent on the shape of the vehicle. The maglev system is highly advantaged in this category because its design could be optimized in terms of aerodynamic performance (cf. section 3.2.3 “Noise Emissions”). No specific vehicle clearance envelope like that which exists for the wheel-on-rail system has to be taken into account. Furthermore, the maglev system does not have any pantographs (power pick-ups) or wheelsets, which are among the main sources of aerodynamic drag on the wheel-on-rail high-speed system (Breimeier, 2002, p. 19). The values of aerodynamic resistance forces of both high-speed ground transportation system provided by both Breimeier and Schach et al. are given in Table 16. For both systems, the values of Schach et al. are somewhat lower than those of Breimeier’s values. All in all, however, the values coincide quite well. Both support the conclusion that maglev has to travel at least 50 km/h (31 mph) faster than wheel-on-rail high-speed trains to be subjected to the same aerodynamic forces in the higher speed ranges.

Table 16: Comparison of Aerodynamic Resistance Forces of Both Systems

Speed [km/h]	Aerodynamic Resistance Forces of the Wheel-on-Rail High-Speed System [kN]		Aerodynamic Resistance Forces of the High-Speed Maglev System [kN]	
	Breimeier (p. 56)	Schach et al. (p. 179)	Breimeier (p. 57)	Schach et al. (p. 180)
100	5.5	5.7	4.0	3.5
150	12.4	12.8	9.2	7.9
200	22.1	22.7	16.3	14.0
250	34.6	35.4	25.5	21.9
300	49.8	51.0	36.8	31.6
350	67.7	61.8	50.0	43.0
400	-	-	65.3	56.1
450	-	-	82.7	71.1

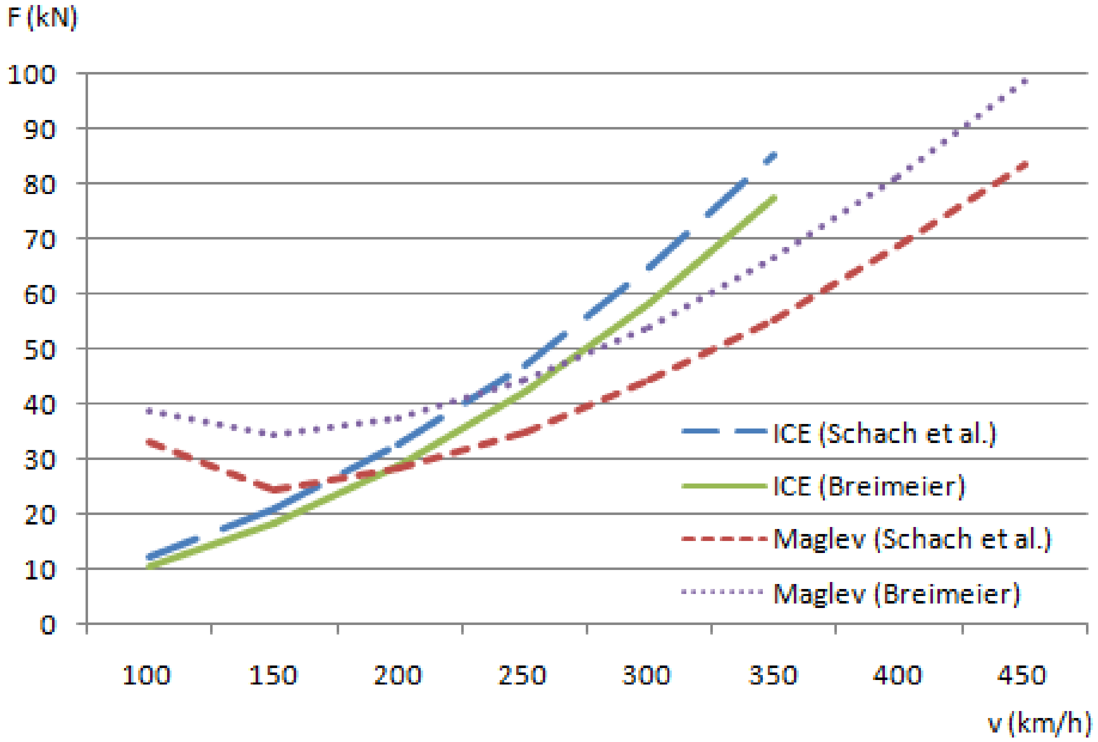
In addition to magnetization resistance and aerodynamic resistance, the high-speed maglev system is subjected to a third kind of resistance. The energy that loads the on-board batteries that feed the on-board support magnets as well as on-board equipment (e.g. heating, air-conditioning, light etc.) is transmitted into the vehicle through electric induction. The power that the support magnets need to make the Transrapid hover is nearly independent of its speed (Schach, Jehle, & Naumann, 2006, p. 182). It can be calculated as a product of the inductive force and the vehicle speed. Accordingly, the required inductive force is lower for higher speeds. This inductive force is the same force that takes effect on the maglev vehicles as a resistance force. Table 17 gives the values of this inductive resistance force according to Breimeier and Schach et al. As mentioned above, this force decrease with increasing speeds.

Table 17: Inductive Resistance Forces of the Maglev System

Speed [km/h]	Inductive Resistance Forces of the High-Speed Maglev System [kN]	
	Breimeier (p. 57)	Schach et al. (p. 180)
100	30.3	26.1
150	19.8	17.3
200	14.5	12.9
250	11.4	10.3
300	9.3	8.6
350	7.8	7.3
400	6.7	6.4
450	5.8	5.6

Furthermore, other resistance forces like those resulting from driving through tunnels may take effect temporarily. Figure 3 shows the values of overall resistance forces for both high-speed ground transportation systems depending on speed.

Figure 3: Comparison of Overall Resistance Forces



According to these values, Breimeier concludes that up to a speed of 265 km/h (165 mph) the ICE 3 wheel-on-rail high-speed train is superior over the Transrapid maglev in terms of overall driving resistance (Breimeier, 2002, p. 20). Corresponding to the values of Schach et al., this break-even point in speed (i.e. the speed which has to be exceeded for the maglev system to show a lower driving resistance than that of wheel-on-rail high-speed system) is approximately 170 km/h (106 mph). It is common for both that driving resistance is lower for the maglev system in the higher speed ranges, i.e. the speed ranges in which the trains travel most of the time. Following Figure 3, resistance forces are lower for the maglev travelling at 300 km/h (186 mph) than those of the wheel-on-rail high-speed ICE traveling at the same speed. However, in case the maglev's speed is increased to 450 km/h (280 mph) its resistance forces exceed those of the wheel-on-rail

ICE at 300 km/h (186 mph). Table 18 shows the relative benefits of the two technologies with respects to driving resistance.

Table 18: Benefit Rating for Driving Resistance

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	4	5	3

1 = Minimum Benefit Value;   5 = Maximum Benefit Value

3.1.9. Integration of Stations into Cities

As pointed out in sections 3.1.5 “Train Weight” and 3.1.6 “Compactness of Train”, a high-speed maglev train is approximately 30 percent lighter per passenger (maglev: 0.56 tons per passenger; wheel-on-rail HSR: approximately 0.8 meters per passenger) and 28 percent shorter per passenger (maglev: 0.29 meters per passenger; wheel-on-rail HSR: approximately 0.4 meters per passenger) than a wheel-on-rail high-speed train. While the lower weight of maglev trains only means that the structure of the station can be a bit lighter, the shorter length of the maglev trains has a more significant impact on station design as platforms can be shorter by the same percentage that the train is shorter. This means a reduction in required land for the station, which can be very beneficial in some inner-city areas having dense development.

Another critical issue with integrating stations into cities is the track that leads to and away from stations. Since they have to be aligned through dense development areas, the more flexible alignment of the maglev system (cf. section 3.1.7 “Flexibility in Track Alignment”) is an advantage. Also the fact that the guideway of a maglev is more suitable for elevated alignment is beneficial for inner-city areas with dense development. On the other hand, the wheel-on-rail high-speed system might be able to use existing conventional railroad tracks to reach city-center locations.

Summarizing the various influences, the maglev system gets a higher benefit rating in this category. Because very high speeds do not apply for approaches to stations, both speed categories (300km/h and 450 km/h (186 mph and 280 mph)) of the maglev system are assigned equal values (cf. Table 19).

Table 19: Benefit Rating for Integration of Stations into Cities

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	3	4	4

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

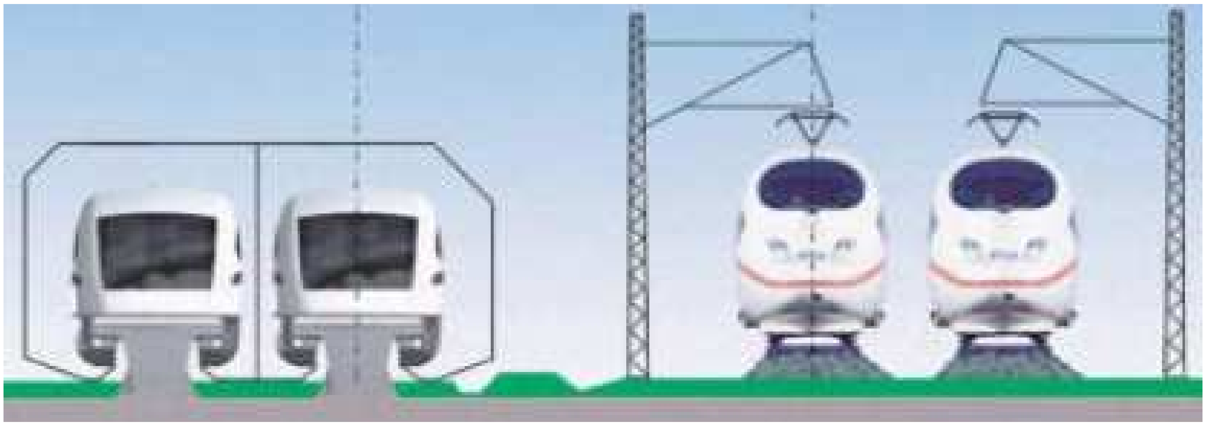
3.2.Environmental Impacts

3.2.1. Land Consumption

The amount of land consumed by a high-speed ground transportation (HSGT) system is dependent on the type of system as well as the way its guideway is constructed. An at-grade track fully consumes the land below the guideway plus additional land on the edges of the track in which signals and the posts for the overhead catenary wires are located. Furthermore, additional land is often needed to build embankments and cuts. An elevated track, on the other hand, only consumes the land which holds the columns supporting the elevated track. The land under an elevated track can still partially be used for other purposes. Other transportation purposes are usually allowed under an elevated guideway, as are other land uses like agriculture. Accordingly, all things being equal, elevated guideways are in most cases superior over at-grade tracks as it relates to land consumption.

Different types of HSGT systems are not equally suitable for at-grade or elevated track designs. As can be seen in Figure 4, the undercarriage of the maglev train wraps around its guideway whereas the rails of the wheel-on-rail train are supported by a ballast substructure that is (after dispensing loads through other layers of different materials) settled on compressed soil.

Figure 4: Cross Section of Tracks of High-Speed Maglev and Wheel-on-Rail High-Speed Systems



(Source: Transrapid International)

According to these specifications, the guideway of a maglev system has an appearance of a beam bridge. To form an elevated track, not much more than just adding columns is necessary. For the most part, the Transrapid maglev route in Shanghai is an elevated guideway (Schwindt, 2004, p. 39).

In contrast, the construction of an elevated guideway for a wheel-on-rail high-speed line is more costly and complex. It is necessary to build an extensive structure that supports the track, its substructure and the posts of the overhead power lines. Besides being wider than an elevated guideway for maglev, these structures also have to be more massive due to the heavier loads that they have to carry (cf. section 3.1.5 “Train Weight”).

For these reasons, European high-speed rail lines that use the wheel-on-rail technology are preferably designed with embankments and cuts instead of elevated tracks. The Spanish AVE high-speed rail line that connects Madrid with Seville, for example, is on embankments that exceed a height of 10 meters (32.8 feet) over approximately 10 percent of the line (López-Pita, Teixeira, Casas, Ubalde, & Robusté, 2007).

Following these considerations, it is assumed that wheel-on-rail high-speed tracks will, if possible, be designed at grade, while maglev tracks will mainly be designed as elevated guideways. Accordingly, a maglev track, on the average, consumes significantly less land for its track than a wheel-on-rail HSR system. In addition, the Transrapid maglev requires no land for access roads for safety or maintenance of the guideway (Siemens, 2006b) (cf. section 3.7.8 “Evacuation of Trains”). Estimates in the differences in land consumption (cf. Table 20) suggest that wheel-on-rail high-speed rail needs between 1.4 times (when both systems are designed at grade) and 25 times (when maglev is designed on an elevated guideway and wheel-on-rail HSR on a 12-meter-high embankment) more land (Schach, Jehle, & Naumann, 2006, p. 93). The values in Table 20 take into account the land needed for technical equipment and power substations. Some of these values also consider ecological mitigation measures that consume additional land.

Table 20: Land Consumption of the Wheel-on-Rail High-Speed Systems and the High-Speed Maglev System

Alignment	Land Consumption for Wheel-on-Rail HSR [m² per m of double track]	Land Consumption for High-Speed Maglev [m² per m of double track]
At-Grade	16.0	11.5
At-Grade plus Mitigation Measures (50%)	24.0	17.0
At a Height of 5 meters	35.0 (track on embankment)	2.0 (elevated guideway)
At a Height of 5 meters plus mitigation measures (50%)	50.0 (track embankment)	3.0 (elevated guideway)
At a Height of 12 meters plus Mitigation Measures (20% for HSR, 50% for maglev)	75.0 (track embankment)	3.0 (elevated guideway)

(Source: Schach, Jehle, and Naumann, 2006, p. 83)

The manufacturer of the Transrapid gives similar values (Siemens, 2006b). Schach, Jehle, and Naumann (2006, p. 94) also conduct an example calculation for the land consumption of a track segment for both systems. Their calculations are based on estimations on the share of the different types of guideway designs on a given track distance. They come to the result that a track for wheel-on-rail HSR consumes on average 4.5 times more land than the guideway of a high-speed maglev system.

In sum, the Transrapid maglev consumes significantly less land for any type of guideway design than wheel-on-rail HSR tracks which leads to the benefit rating shown in Table 21.

Table 21: Benefit Rating for Land Consumption

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	2	5	5

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.2.2. Energy Consumption

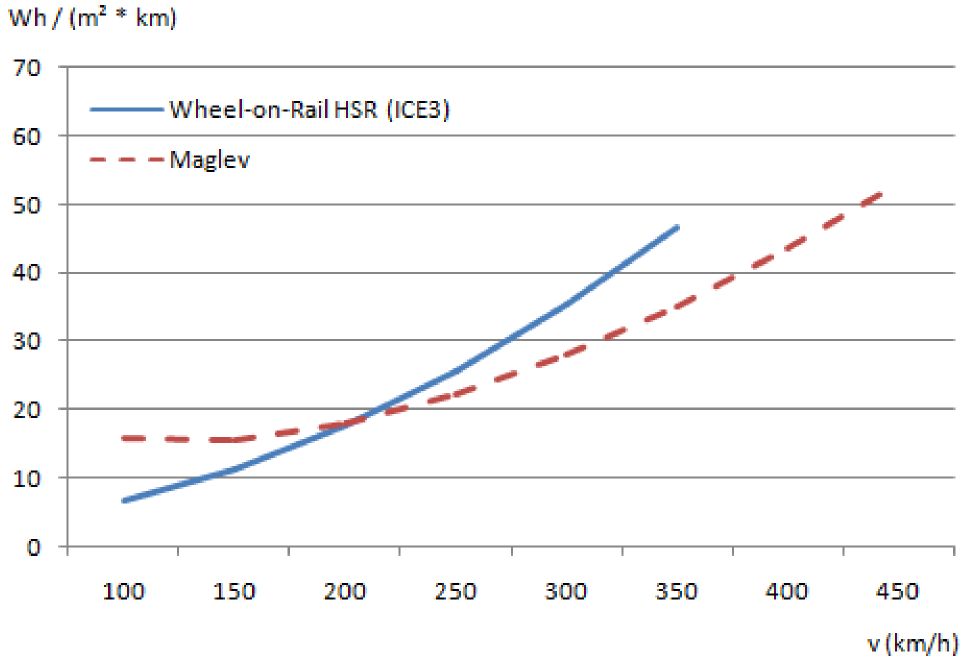
Energy prices have been rising over the last decade and most energy experts believe that fossil fuel sources are limited. The combustion of fossil fuels is also recognized as a major reason for global climate change. The transportation sector is a major source of greenhouse gases, with these emissions steadily increasing (Smith, 2003). This is why new technology development in the transportation sector should support decreasing energy consumption. New transportation systems should facilitate the usage of renewable resources. Because both electrified wheel-on-rail high-speed trains and high-speed maglev trains consume electric energy, they could both be based on a sustainable energy supply, depending on how the electrical energy is produced.

According to Givoni, Brand, and Watkiss (2009, pp. 6-7), energy consumption is mainly dependent on the train technology, the geographical characteristics of the route (flat vs. mountainous), and the spacing of intermediate stops along the route. The latter is probably the one factor affecting energy consumption that operators have most control over. Operators have to make a tradeoff between making the high-speed rail system available to more passengers by stopping at more stations or decreasing travel times and energy consumption by stopping at fewer stations. This matter is also the cause for some disagreement among different authors concerning the energy consumption of the two high-speed systems.

Furthermore, there is no agreement on which physical parameter energy consumption should be related to. Breimeier (2002, p. 21) argues that the energy consumption per square meter of floor space should be used since this is a “technical-physical” measure that cannot be modified by applying a different seating layout. Schach, Jehle, and Naumann (2006, p. 196), however, are in favor of relating the specific energy consumption to number of seats because this figure is directly related to the actual passenger transportation capacity of each train system. According to them, the calculation based on floor space is more questionable since this figure can disguise the fact that not all the floor space can be equally well used for seating.

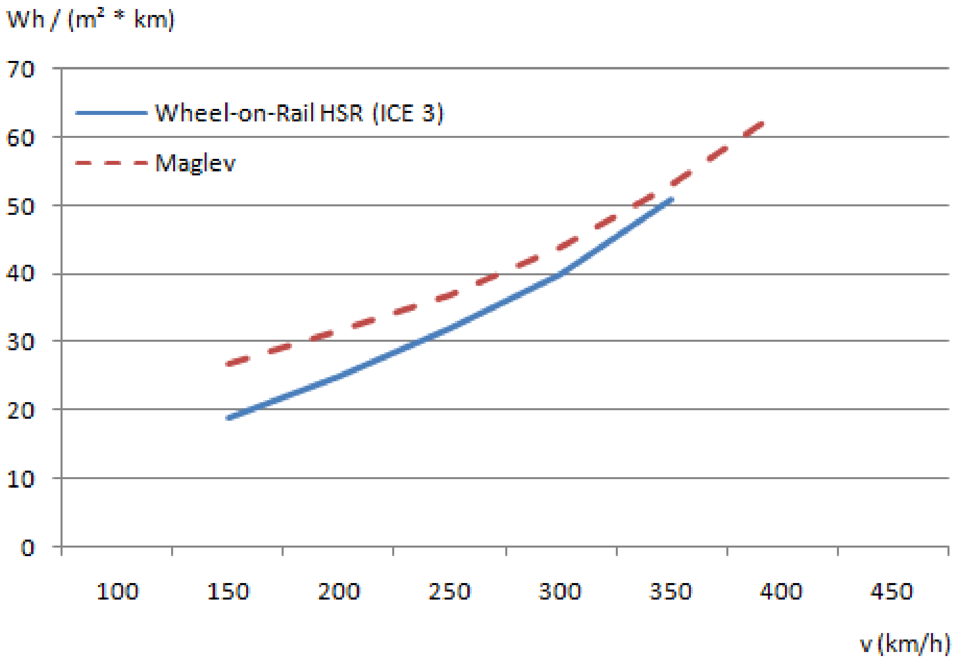
The conclusions in this thesis are based on a combination of both approaches. First, the specific energy consumption with respect to square meters of floor space and travelled kilometers is examined. Both Breimeier (2002, p. 21) and Schach, Jehle, and Naumann (2006, pp. 193-198) state that the relative increase in energy consumption with speed is lower for the Transrapid maglev system in the range of higher speeds due to its lower aerodynamic drag. However, the authors give different absolute values for the specific energy consumption at different speeds. According to Breimeier, the energy consumption of the Transrapid maglev is higher that of the ICE 3, the newest German wheel-on-rail high-speed train, for any speed (cf. Figure 5). Schach, Jehle, and Naumann, however, say that from about 200 km/h (124 mph) on, the high-speed maglev train consumes less energy than the wheel-on-rail high-speed train (cf. Figure 6). These differences mainly result from different underlying assumptions. Breimeier, being a critic of maglev systems, uses rather pessimistic assumptions. The assumptions of Schach, Jehle, and Naumann tend to be rather positive toward the maglev system.

Figure 5: Energy Consumption per Square Meters of Floor Area per Kilometer (Breimeier)



(Source: Breimeier, 2002, p. 21)

Figure 6: Energy Consumption per Square Meters of Floor Area per Kilometer (Schach et al.)

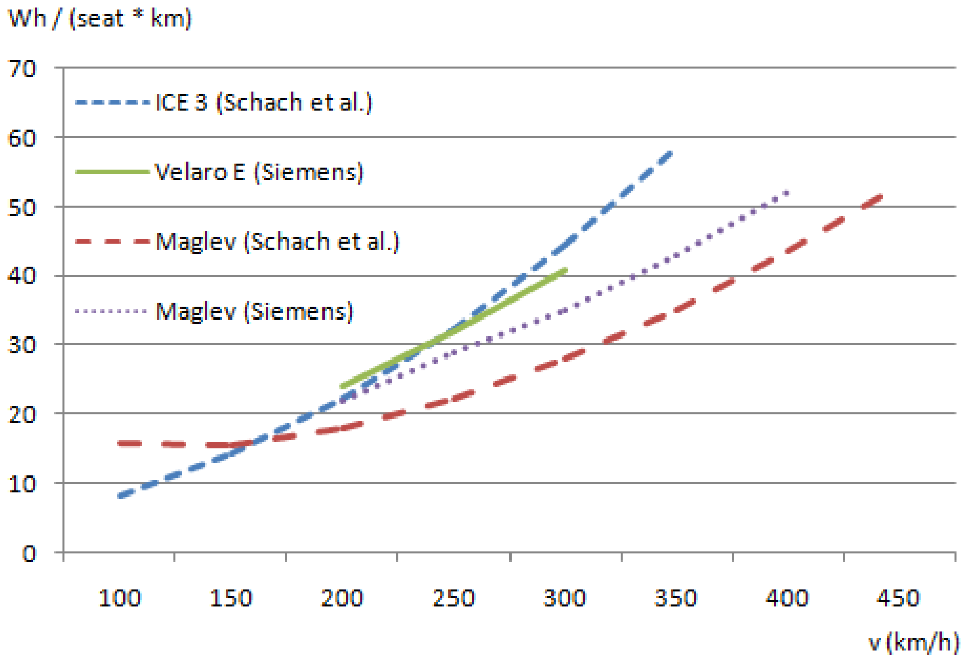


(Source: Schach, Jehle, and Naumann, 2006, p. 198)

Because a disproportionally high share of energy is consumed during train acceleration, the energy consumption per kilometer is dependent on assumptions about the average distance between stops. Breimeier uses 73 kilometers for this parameter since this value represents the average stop distance in the current German long-distance intercity network (Breimeier, 2002, p. 58). Applying these considerations to the United States, the average distance between stops needs to be increased since major cities in the USA are significantly farther away from one another than major cities in Germany. Only in the Northeast Corridor are population densities similar to those in Germany.

Applying the measure of specific energy consumption relating to seats and kilometers, results similar to those in Figure 5 are found. From a speed of approximately 160 km/h (99 mph), the specific energy consumption of the maglev per seat per kilometer is lower than that of wheel-on-rail high-speed rail. The values in Figure 7 are drawn from the comparison between the German ICE 3 wheel-on-rail high-speed train and the Transrapid high-speed maglev by Schach, Jehle, and Naumann (Schach, Jehle, & Naumann, 2006, p. 196) and from manufacturer’s information on the Spanish Velaro E wheel-on-rail high-speed train and the Transrapid high-speed maglev (Siemens, 2006a) (Siemens, 2006b, p. 7). As pointed out, the values by Schach, Jehle, and Naumann tend to be too optimistic. The manufacturer gives higher values for the energy consumption of the Transrapid maglev. While the manufacturer’s values for the Transrapid are approximately 4-5 watt-hours per seat per kilometer higher, the observation that the Transrapid maglev shows lower energy consumption values from speeds higher than approximately 175 km/h (109 mph) stays the same. The values of the two wheel-on-rail high-speed trains (the German ICE 3 and the Spanish Velaro E), however, coincide very well. This is arguably true to the fact that the Velaro E was developed on the basis of the ICE 3. The values from Figure 7 confirm Rausch’s (2004, p. 26) statement that the Transrapid maglev consumes approximately the same amount of energy at a speed of 400 km/h (249 mph) as the wheel-on-rail ICE 3 at a speed of 300 km/h (186 mph).

Figure 7: Energy Consumption per Seat per Kilometers



(Sources: Schach, Jehle, and Naumann, 2006, p. 196; Siemens, 2006a; Siemens, 2006b, p. 7)

Considering the above results, one has to conclude that for higher speeds (exceeding approximately 175 km/h (109 mph)) the specific energy consumption of the maglev (no matter if calculated per square meters of floor space or per seat) is lower. Therefore, a higher benefit rating for the energy consumption at 300 km/h (186 mph) has to be assigned to the maglev system. For travel speeds of 450 km/h (280 mph), the energy consumption of the maglev is a bit higher than that of the wheel-on-rail high-speed trains at 300 km/h (186 mph) (cf. Table 22).

Table 22: Benefit Rating for Energy Consumption

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	3	4	2

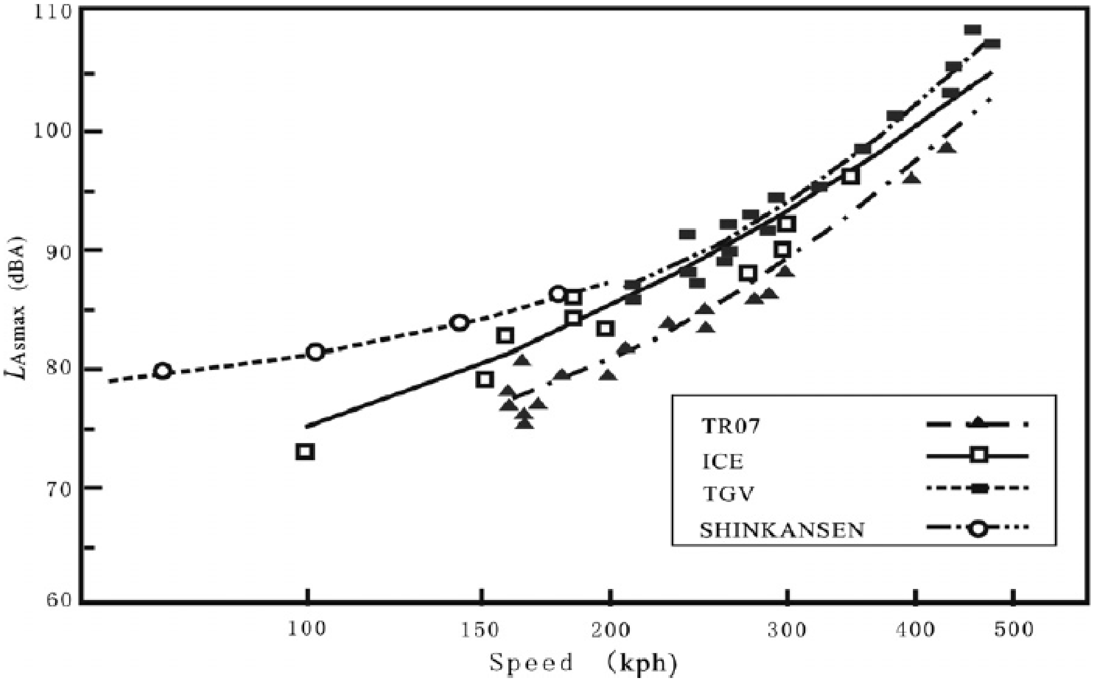
1 = Minimum Benefit Value;   5 = Maximum Benefit Value

3.2.3. Noise Emissions

Noise emissions can be categorized into three groups: 1) Noise that results from propulsion or machinery noise, 2) mechanical noise that comes from wheel-rail interactions and/or guideway vibrations, and 3) aerodynamic noise. For lower speeds (i.e. speeds below approximately 200 km/h (124 mph)) propulsion and mechanical noise are dominant. For higher speeds, aerodynamic noise becomes the main source of noise (Chen, Tang, Huang, & Wang, 2007). Because any physical contact is eliminated in the maglev system, mechanical noise does not exist for maglev trains, which is advantageous at lower speeds. Thus, a maglev train can approach an urban terminal in a densely populated city center with higher speeds than a wheel-on-rail high-speed train (cf. section 3.5.5 “Achievable Speeds in Urbanized Areas”).

For the higher speeds achieved on the main portion of long-haul trips, aerodynamic noise emissions are the only ones that have to be considered. Figure 8 depicts noise levels at a distance of 30.5 meters of different HSGT systems as analyzed by Chen, Tang, Huang, and Wang (2007) on the Shanghai maglev system. It can be seen that the Transrapid maglev train emits less noise than the three wheel-on-rail high-speed system (i.e. the German ICE, the French TGV, and the Japanese Shinkansen) considered in the study.

Figure 8: Noise Emissions of different High-Speed Ground Transportation Systems at a Distance of 30.5 meters dependent upon Speed



(Source: Chen, Tang, Huan, and Wang, 2007, p. 440)

The values of Figure 8 coincide well with values for the ICE 3 given by Schach, Jehle, and Naumann (2007, p. 142) and Rausch (2004, p. 25) shown in Table 23. These values have been measured at a distance of 25 meters (82 feet) from the respective guideways. The noise emissions of the Spanish Velaro E AVE are very similar to those of the German ICE 3 (e.g. 91 dB at 300 km/h (186 mph) as compared to 90 dB for the ICE 3 at 300 km/h (186 mph)). However, the values for the maglev system by Schach et al. and Rausch are lower than those by Chen, Tang, Huang, and Wang who derive their values from measurements on the Shanghai maglev system. Because this track is in commercial operation, these values will be considered more strongly. Despite the differences in the absolute-number values for the high-speed maglev system, all studies agree that noise emissions of the maglev system are considerably lower for any given speed than those of wheel-on-rail high-speed system.

Table 23: Noise Emissions of different High-Speed Ground Transportation Systems

	200 km/h	300 km/h	400 km/h
ICE 3 (Series 403)	85 dB	90 dB	-
Transrapid (Series TR 08)	73 dB (75 dB)	80 dB	91 dB (90 dB)

(Source: Schach and Naumann, 2007, p. 142; and values in parentheses Rausch, 2004, p. 25)

Besides noise levels, Chen, Tang, Huang, and Wang (2007) also found through a survey that onset rates of noise levels are also critical for residents adjacent to railway lines. Onset rates describe how fast (decibels per second) noise levels increase. The higher the onset rates, which are dependent on travel speeds, the more annoyed were residents by traffic noise. For equal speeds, the maglev performs better than any of the wheel-on-rail high-speed trains since its noise levels are lower while onset rates are the same. However, if the maglev train is operated with speeds that exceed the speeds that wheel-on-rail high-speed trains can achieve, both noise levels and onsets rates increase significantly so that more noise protection becomes necessary.

In general, the emissions of aerodynamic noise are dependent on aerodynamic drag. The high-speed Transrapid maglev is, due to its better aerodynamic design, superior over wheel-on-rail high-speed in terms of aerodynamic noise emissions at a given travel speed (cf. section 3.1.8 “Driving Resistance”). This fact might raise the question of why the design of wheel-on-rail high-speed trains is not more a similar to that of maglev trains. The problem is that the potential for streamlined design for conventional high-speed trains is largely depleted. The width of a train is constrained by the standard track gauge of 1,435mm (4 ft 8½ in), which prevents a wider, but flatter design to the trains. Furthermore, an electrically-driven wheel-on-rail high-speed train needs to have a pantograph (power pickup) to be supplied with electricity. These features as well as the wheelsets are among the main sources of aerodynamic noise and the potential for aerodynamic optimization of these features is largely depleted. According to the results from above, the benefit ratings for noise emissions are assigned in Table 24 to reflect the relative noise levels emitted by both high-speed systems.

Table 24: Benefit Rating for Noise Emissions

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	3	5	2

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.2.4. Interference with the Natural Environment

As discussed in section 3.2.1 "Land Consumption", it is assumed that maglev systems are normally aligned on elevated guideways whereas the normal alignment for wheel-on-rail high-speed systems is at grade. Since the areas where soils need to be compressed are smaller for elevated guideways, the natural water balance is in general less disturbed in the vicinity of elevated guideways than near tracks that are designed at grade. According to Gers, Hübner, Otto, & Stiller (1997, pp. 6-8) approximately 180,000 cubic meters of earth per kilometer of double track (378,809 cubic yards per mile of double track) track have to be moved for a typical wheel-on-rail high-speed track in flat topography, while for a maglev guideway in a similar environment this figure is only a quarter as high (cf. 3.2.10 "Material and Resource Consumption"). The extent of earth-moving gives a good impression on the amount of interference with the natural environment.

According to tests at the Emsland Test Facility (TVE) in Germany, no airflows were detected below the elevated maglev guideway when a maglev train passed by (Siemens, 2006b, p. 9). Alongside the maglev guideway an air flow speed of 10 km/h

(6.2 mph)[15] was measured when the maglev train passes by with a speed of 350 km/h (218 mph).

Furthermore, the separation impact of an elevated guideway is lower. “An elevated guideway helps to preserve areas that are ecologically sensitive or part of a connected agricultural area. […] The guideway can be easily adapted to any terrain, with minimal influences on plants and wildlife (Siemens, 2006b, p. 19).” Animals can cross below the track so that natural habitats are less disturbed. For at-grade tracks this is not possible; measures specifically designed to enable animals to cross the guideway are necessary. In European countries, where environmental regulations are particularly stringent, major attention is paid to environmental impacts of transportation systems. Therefore, various solutions to mitigate the negative effects of at-grade railway tracks have been developed. For example, wildlife crossings that reconnect separated habitats are commonplace for highway and railway projects. Also extensive measures are used to reestablish the natural water balance that has been disturbed through the implementation of a major construction project. If these measures are effectively applied, interference with the natural environment can be minimized.

As pointed out, however, an elevated system is more environmentally friendly in the first place so that much less of the abovementioned mitigation is necessary. Therefore, a higher benefit rating for interference with the natural environment is assigned to the maglev system as shown in Table 25.

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[15] 10 km/h (6.2 miles) equals approximately 5.4 knots which the Beaufort Wind Scale defines as a “light breeze”; http://www.spc.noaa.gov/faq/tornado/beaufort.html Accessed June 17, 2010

Table 25: Benefit Rating for Interference with the Natural Environment

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	2	4	4

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.2.5. Suitability for Co-Alignment with other Transportation Infrastructure

A major part of the total track distance of the new Florida high-speed rail system is planned to be aligned along Interstate 4 (I-4). From an environmental perspective, a co-alignment of different transportation infrastructure is preferable since no further natural habitats are usually affected. Not every high-speed transportation system, however, is equally suitable to be co-aligned. Interstate highway design standards (AASHTO, 2005) mandate a minimum horizontal curve radius of 600 meters (1968 feet). A co-alignment of either of the two HSGT systems with an interstate highway where the minimum radius of 600 meters is applied would force extremely reduced speeds. According to section 3.1.7 “Flexibility in Track Alignment” a speed of 200 km/h (124 mph) is for the Transrapid high-speed maglev achievable in curves with a radius of 900 meters (2953 feet). Wheel-on-rail high-speed trains need a minimum curve radius of 1,500 meters (4921 feet; i.e. 67 per cent higher than maglev) to be able to travel at 200 km/h (124 mph). This means that a co-alignment with design speeds of 200 km/h (124 mph) is more easily achievable with the maglev system. This can be particularly useful for approaches to stations in city centers where land use is very constrained.

If a higher travel speed is desired than that allowed by the curve radius of an interstate highway, the new infrastructure will be forced to diverge from the existing infrastructure in that section (alternatively one can also consider changing the existing infrastructure). Especially in cases where the new HSGT system travels in the median of an interstate highway, diverging from the existing infrastructure is a very complicated problem that usually requires bridge structures on which the new HSGT track crosses the lanes of the existing interstate highway. This can obviously be more easily achieved with an elevated guideway. Since the maglev system is much more suitable for an elevated guideway, co-alignment on the median of an interstate is easier for a maglev system.

In summary, due to its lower minimum curve radii a maglev system is more desirable for co-alignment with existing transportation infrastructure like interstate highways. Furthermore, complicated design problems in which the new infrastructure has to diverge in alignment from the existing infrastructure can be more easily handled with a maglev system (cf. Table 26).

Table 26: Benefit Rating for Co-Alignment with Existing Transportation Infrastructure

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	2	4	2

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.2.6. Need for Construction of Structures (Bridges, Tunnels)

The need for the construction of artificial structures like bridges and tunnels is to a large extent dependent on the capability of the guideway to fit into a given topography. In Section 3.1.7 “Flexibility in Track Alignment” it was shown that the maglev system can handle lower minimum radii for horizontal curves and higher maximum slopes at a given speed. This leads to the conclusion that a high-speed maglev guideway can be more easily integrated into a given topography than a wheel-on-rail high-speed track, which results in a lower number of required structures like bridges and tunnels (Siemens, 2006b, p. 19).

The planning of a high-speed line between Dresden in the eastern part of Germany and the Czech Republic, for instance, showed the differences in the need for construction of structures between the two high-speed systems. The alignment would have to cross a lower mountain range. Under the premise of a design speed of 300 km/h (168 mph) a 9.4-kilometer-long tunnel would be necessary for the wheel-on-rail high-speed system. The maglev system, on the contrary would not need any tunnel for the same speed. For a design speed of 400 km/h (249 mph) the maglev system would need a 3.7-kilometer-long tunnel (Fengler, 2004).

In summary, a maglev track in general requires a smaller number of structures than a track of the wheel-on-rail high-speed system. This is particularly important in hilly or mountainous terrain. Table 27 shows the benefit ratings for both technologies.

Table 27: Benefit Rating for Need for Construction of Structures

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	2	5	3

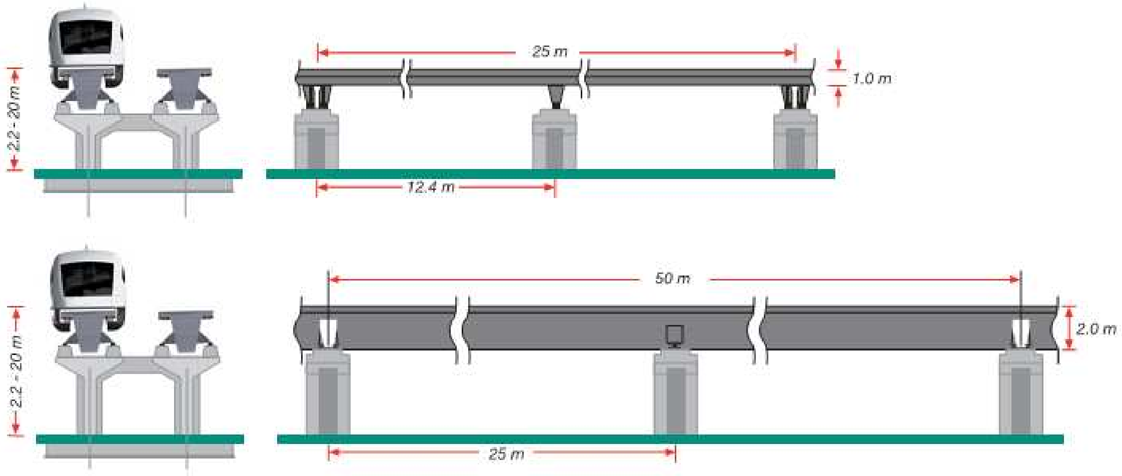
1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.2.7. Aesthetic Impacts on Landscape and Cityscape

Within a city an elevated guideway is obviously more visible than an at-grade guideway. So, an elevated guideway separates the cityscape to a larger extent than does an at-grade guideway. However, because a maglev travelling at a speed of 200 km/h (124 mph) emits a noise of 73.5 dB it is not significantly louder than the rule-of-thumb value for normal road traffic (70 dB) (Siemens, 2006b). This means that for a maglev up to a speed of 200 km/h (124 mph) (in less constrained environments even higher), no noise barriers are required. The only visual obstructions due to a maglev guideway are the beams and the columns of the guideway. There are no overhead catenary wires or posts for these that further visually divide the cityscape. The height of the guideway beams and thereby the extent of the aesthetic impact is dependent on the length of these beams (i.e.

the distance between two columns that support the elevated guideway). Guideway beams of a length of 12.4 meters (40.7 feet) have a height of approximately 1 meter (3.3 feet) (cf. Figure 9) and thereby only cause a rather limited visual division. By using these beams, the passage below the guideway between two supporting columns is approximately 11 meters (36 feet) wide. This is usually wide enough for a local or a collector road.

Figure 9: Geometry of Guideway Beams for Elevated Maglev Track



(Source: Transrapid International, 2006, p. 8)

In the open countryside an elevated guideway is visible from longer distances. However, as explained in sections 3.1.7 “Flexibility in Track Alignment” and 3.2.6 “Need for Construction of Structures (Bridges, Tunnels)” a lower percentage of a maglev guideway will have to be placed on bridges, which are a major component of visual impact.

In sum, the two systems can be considered approximately equal in terms of visual impact for both a city and the open countryside (cf. Table 28).

Table 28: Benefit Rating for Aesthetic Impacts on Landscape and Cityscape

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	3	3	3

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.2.8. Barrier Effect (Physical Separation of Landscape and Cityscape)

As pointed out in section 3.2.1 “Land Consumption”, maglev systems will be constructed as elevated guideways for the main portion of the total track length. It is largely accepted that the elevated guideway is advantageous in terms of physical separation of landscape and cityscape (Schach & Naumann, 2007, p. 144). Physical separation (contrasting visual separation; cf. section 3.2.7 “Aesthetic Impacts on Landscape and Cityscape”) describes how people, animals and other modes of transportation are impaired by the implementation of a certain guideway into a cityscape or landscape. This is why physical separation is often called the ‘barrier effect’.

The concern about barrier effects due to transportation infrastructure became concern in the United States in the sixties and seventies when whole neighborhoods were being divided because of the construction of the interstate highway system that was, in contrast to highway systems in most European countries, located through cities. There are many famous examples were whole quarters of cities fell into an economic and social decline after they had been physically separated from the rest of the city by an interstate highway. Among these examples are the waterfronts of San Francisco (Embarcadero Highway) and Boston (Central Artery). In order to reverse the barrier effects, major projects had to be conducted. The Embarcadero Highway in San Francisco was torn down in 1991; the Central Artery in Boston was relocated into a tunnel. This project, commonly known as “The Big Dig”, was the most expensive highway project in history.

The standard guideway beams for the maglev have lengths of either 12.4 meters (40.7 feet) or 25 meters (82 feet). As has been pointed out in section 3.2.7 “Aesthetic

Impacts on Landscape and Cityscape" the 12.4-meter guideway beams allow for an approximately 11 meter (36 feet) wide passage below the guideway between two adjacent supporting columns. This is usually wide enough for a local or a collector road. The longer 25-meter (82 feet) guideway beams allow for the passage of a multilane arterial road below the maglev guideway without locating a supporting column in the median of the roadway. As such, dedicated crossover constructions like bridges or underpasses are unnecessary. This is an advantage because pedestrian and bicyclist underpasses are often disliked for reasons of perceived safety. Because crossover structures are expensive, just as many as necessary will be constructed thus causing people to use more circuitous routes to reach areas on the other side of the track. This is why an at-grade guideway usually has a major barrier effect on landscapes and cityscapes. They separate cities physically whereas an elevated maglev guideway for the main part is just a visual division that has been dealt with in section 3.2.7 "Aesthetic Impacts on Landscape and Cityscape". Table 29 shows the benefit values that have been assigned for barrier effects.

Table 29: Benefit Rating for Barrier Effects (Physical Separation)

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	2	4	4

1 = Minimum Benefit Value;   5 = Maximum Benefit Value

3.2.9. Vibration

Due to the lack of physical contact during operation, a passing maglev train causes much less vibration than a wheel-on-rail high-speed train. The significance of higher amounts of vibrations of wheel-on-rail trains is further increased by the higher weight of these trains as compared to maglev trains. According to Rausch (2004, p. 25), maglev shows "appreciably lower vibration levels than wheel-on-rail trains". He argues that the vibration emitted by a maglev at travel speeds of 400 km/h (249 mph) lie below those of a conventional train travelling at approximately 135 km/h (84 mph). At a speed of 250 km/h (155 mph) and a distance of 25 meters (82 feet) the vibration caused by the Transrapid is below the human perception level. At a distance of 50 meters (164 feet), no vibration is noticeable at all (Siemens, 2006b, p. 9). Therefore, maglev systems have to be seen as superior in terms of avoidance of vibrations over wheel-on-rail high-speed trains (cf. Table 30).

Table 30: Benefit Rating for Vibration

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	2	5	4

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.2.10. Material and Resource Consumption

Materials and resources are, one the one hand, consumed for the initial construction of the HSGT system and, on the other hand, during the rest of the lifecycle of the system. Giving general values for material and resource consumption is very difficult since these values underlie a high range of variation dependent on a specific project. Gers, Hübner, Otto, and Stiller (1997, pp. 6-8) chose sample plannings of either HSGT system that they consider very typical for either HSGT system. To ensure the fairness of the comparison both plannings are located in a similar, flat topography. The material and resource consumptions (per kilometer of two-directional track) of the two technologies are shown in Table 31.

Table 31: Comparison of Material and Resource Consumption

	Track for Wheel-on-Rail High-Speed System (ICE 3; flat topography) [per kilometer of double track]	Guideway for High-Speed Maglev (Transrapid; flat topography) [per kilometer of double track]
Earth Moving	182,962 m³	43,584 m³
Ballast	25,539 m³	63 m³
Gravel	-	4,346 m³
Concrete	2,388 tons	4,653 tons
Steel	2,100 tons	1,796 tons
Aluminum	-	20 tons
Bitumen	1,979 m³	-
Geotextile	12,024 m²	-

While the amount of steel consumption for the initial construction of the tracks for both systems is in a similar range, needs for other materials differ significantly. The extent of earth-moving is approximately four times higher for a wheel-on-rail high-speed track than for a maglev guideway in a comparable, flat topography. The consumption of concrete, on the other hand, is about twice as high for the maglev system. Furthermore, for the guideway magnet 20 tons of aluminum per kilometer of double track are necessary. The consumption of other materials like ballast, bitumen, and geotextile is only significant for the wheel-on-rail system.

Schach, Jehle, and Naumann (2006, p. 136) also mention the above figures. They additionally take into account the percentage of tunnels over a certain track distance. As pointed out in section 3.1.7 “Flexibility in Track Alignment”, the maglev system has a higher flexibility in alignment so that it requires fewer tunnels. Since said comparison has been tailored to the mostly hilly topography of Germany, a percentage of tunnels of 30 percent for the wheel-on-rail system have been assumed. Due to the better flexibility in alignment this figure is only 5 percent for the maglev system. Since a high share of tunnels increases the overall consumption of concrete significantly, Schach, Jehle, and Naumann give values of consumption of concrete in hilly terrain of 27.7 m³ (12.0 tons) per kilometer of two-directional track for the wheel-on-rail system and 5.7 m³ (2.5 tons) per kilometer of two-directional track for the maglev system. These results lead the authors to the conclusion that “in almost all fields the material consumption of the Transrapid is lower as for the wheel-on-rail system.” (Schach, Jehle, & Naumann, 2006, p. 135).

The underlying assumptions, however, do not hold true for the United States because of the different topography. Except for the flatlands in the northern part of the country, Germany is mostly hilly. The continental United States, including some of the more densely populated regions, is mainly flat so that in many regions no tunnels would be necessary. This is why the conclusions in this thesis on the values of Table 31. While the wheel-on-rail system consumes more materials in general, the maglev system consumes higher amounts of more expensive materials. Therefore, the overall benefit rating is assumed approximately equal between the two systems (cf. Table 32).

Table 32: Benefit Rating for Material and Resource Consumption

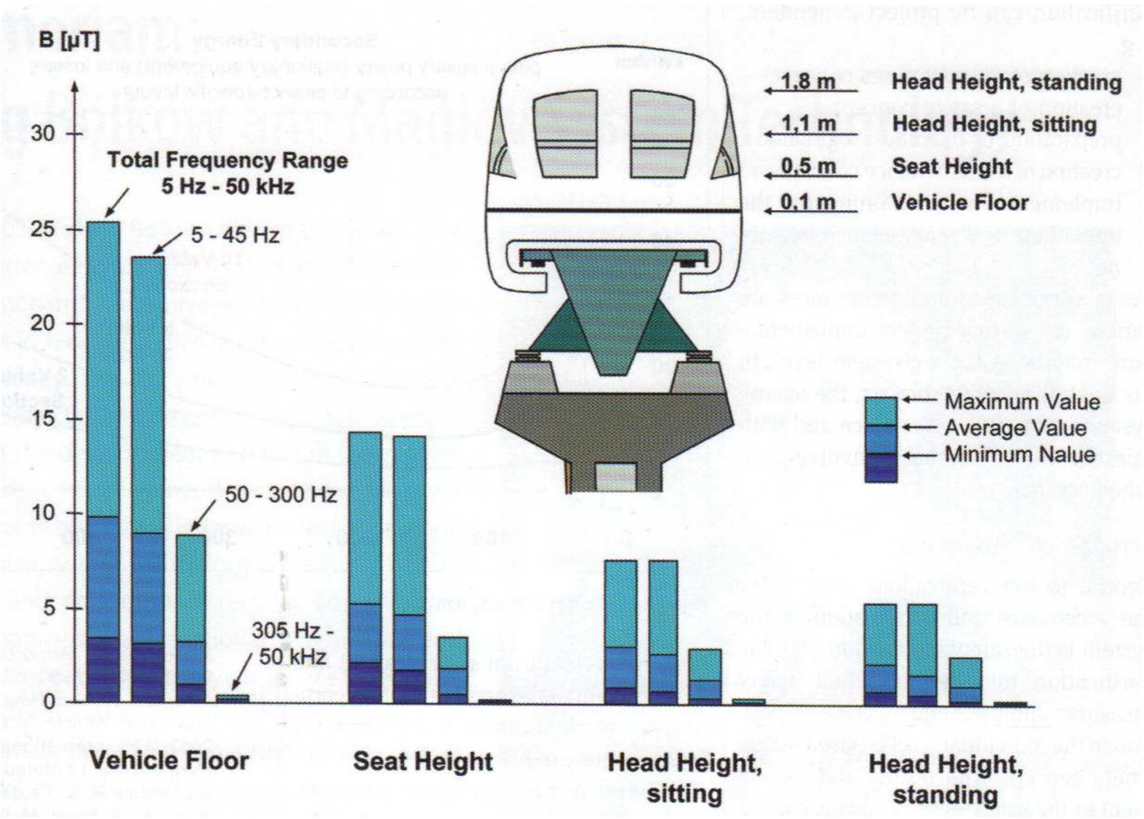
	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	3	3	3

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.2.11. Electromagnetic, Magnetic, and Electric Fields

According to Rausch (2004, p. 26), the magnetic fields in the Transrapid vehicles and along the route are significantly below human health threshold values. This is equally true for the electric and electromagnetic fields. Effects on the health of passengers, staff and third parties are minimal. People who have heart pace-makers can ride the Transrapid maglev without any restriction. Because the gap between the propulsion magnets in the guideway and the support magnet on the vehicle is only 10 millimeters (0.4 inches), the magnetic fields are very concentrated. Outside the gap the strength of the magnetic field decreases rapidly. “Several research studies, including reports from the Research Institute for Energy and Environmental Technology commissioned by Germany’s Federal Institute for Occupational Medicine, confirmed that electromagnetic fields over the Transrapid’s entire frequency spectrum are significantly lower than permissible limits set by Germany’s Federal Emissions Regulation. There are thus no adverse effects on pacemakers or magnetic cards (Siemens, 2006b, p. 7).” Figure 10 shows the strength of magnetic fields at different locations inside the vehicle. For comparison, the magnetic field around a low-voltage halogen desk lamp usually exceeds 4.5 μT. The magnetic field in a distance of 0.5 meters (1.64 feet) from a television (with cathode ray tube) is approximately 3.5 μT.

Figure 10: Strength of Magnetic Fields at different Locations inside the Vehicle



(Source: Rausch, 2004, p. 29)

Contrary to the Transrapid maglev that is based upon electromagnetic levitation, the Japanese MLX01 (JR-Maglev), which is based on electrodynamic levitation, has stronger leakage fields. Because the gap between the guideway and the vehicle in the Japanese MLX01 is significantly bigger (100 millimeters – 3.94 inches), magnetic fields inside the vehicle are very strong. Accordingly, people with heart pace-makers are not allowed to ride this system. Also, credit cards and other devices that are sensitive to magnetic fields must not be carried on the vehicle.

According to Brecher (2004), the magnetic fields inside the Transrapid TR08 (the model that is used on the commercially operated track in Shanghai) are comparable to magnetic fields on the French TGV Atlantique wheel-on-rail high-speed train as well as some American trains. However, because magnetic fields are higher on maglev trains than on most of the wheel-on-rail high-speed trains, the benefit values in Table 33 are assigned.

Table 33: Benefit Rating for Electromagnetic, Magnetic, and Electric Fields

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	4	2	2

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.2.12. Pollutant Emissions

Different kinds of emissions and pollutions occur over the lifetime of a transportation system. First, emissions are discharged when raw materials for train and track are extracted, followed by emissions during the production or construction processes. Also emissions occur when trains are recycled. However, the most long-lasting and easiest-to-calculate emissions occur during operation. To quantify pollutant emissions, carbon dioxide (CO_2) is usually used as the main indicator. Other greenhouse gas (GHG) pollutants relevant to ground transportation include nitrous oxide (N_2O) and methane (CH_4). These have an even higher global warming potential per mass of pollutant than CO_2. However, they are emitted in much smaller quantities. Also, data on CO_2 emission are more readily available (Givoni, Brand, & Watkiss, 2009, pp. 1-2).

All high-speed ground transportation systems are highly advantageous over air travel in terms of pollution. Givoni, Brand, and Watkiss (2009, p. 8) mention a study conducted by the administration of the Eurostar[16] high-speed-rail system that assessed CO_2 emissions for trips between London and Paris by airplane and by the Eurostar high-speed train. Travelling by aircraft, 168 grams of CO_2 (gCO_2) are emitted per passenger-km, while travelling by Eurostar high-speed train emits only 17 gCO_2 per passenger-km. This figure is based on today's electricity generation mix in the United Kingdom and France. Assuming that instead of the general UK energy mix, this calculation was based on the energy mix of British Energy (BE) that has (like the French energy mix) a higher share of nuclear energy, only 11 gCO_2 per passenger-km would be emitted. According to the authors these values match well with figures derived from reports by the British government.

For diesel trains, the emissions can directly be calculated with regard to fuel consumption, type of fuel, and installed fuel gas treatment. For electrified train systems, by contrast, emissions and pollutions occur indirectly at the power plant. That is why "electric trains have virtually zero impact on local air quality at point of use, i.e. alongside the rail network (Givoni, Brand, & Watkiss, On the right track? The role of rail tackling climate change, 2009, p. 4)." Pollution only occurs at the point of electricity generation, which is usually away from densely populated areas resulting in relatively low impacts when compared to urban areas.

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[16] The Eurostar high-speed passenger service connects London with Paris and Brussels and crosses under the English Channel via the Channel Tunnel.

The overall amount of CO_2 emissions is determined by primary power needs and the raw materials used to create and distribute electrical power (Siemens, 2006b, p. 7). Accordingly, the CO_2 content of electricity is dependent on the mix of primary energies used to generate electricity (coal, gas, nuclear, renewable (e.g. wind, hydro, solar), oil). Table 34 shows the amounts of CO_2 that are emitted to produce one kilowatt-hour of electricity.

Table 34: CO_2 Content of Different Forms of Electricity

Coal [gCO_2/kWh]	Oil [gCO_2/kWh]	Gas [gCO_2/kWh]	Nuclear [gCO_2/kWh]	Renewable [gCO_2/kWh]
876	590	370	16	0

(Source: Givoni, Brand, and Watkiss, 2009, p. 5)[17]

In the United Kingdom, for example, "the operation of electric trains […] results in significantly less CO_2 emissions than for diesel operation. […] While passenger transportation by electrified trains caused the emission of 54 gCO_2 per passenger-km, passenger transportation by diesel train caused 69 gCO_2 per passenger-km(Givoni, Brand, & Watkiss, On the right track? The role of rail tackling climate change, 2009, p. 2). As pointed out, this figure is dependent of the mix of primary energy sources used to generate electricity, which is given in Table 35.

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[17] The data for coal, oil, and gas was obtained from the British Department for Business & Regulatory Reform. The data for nuclear energy was obtained form a study by the "Sustainable Development Commission". For renewable energy sources the common assumption of zero emission was adopted

Table 35: Primary Energy Sources for Electricity Generation in different Countries

Country	Coal [%]	Oil [%]	Gas [%]	Nuclear [%]	Renewable [%]
United Kingdom [18]	33.3	1.2	40.2	20.2	3.7
United States [19]	51	1	17	21	9
France [20]	4.5	1.0	3.7	78.3	11.5
Czech Republic [21]	58.8	0.3	5.6	31.2	3.3

Combining the information on the CO_2 contents of different sources of primary energy from Table 34 and the information on primary energy mixes from Table 35, we can calculate that the generation of one kilowatt-hour of electricity in the United Kingdom causes 451 grams of CO_2. For the United States this figure is 519 grams of CO_2, about 15 percent higher. Given these considerations, operating electrified trains in the United States causes a 10 percent lower CO_2 emission than operating diesel trains, on the average, while in the United Kingdom operating electrified trains causes about 20 percent less CO_2 emissions.

This is why Thornton (Thornton, 2009) argues that in the United States, "the emission rates of electrified systems still show values that are not much lower than those of systems that directly get their propulsion energy from fossil fuels". He argues that this because today's generation of electric energy in the United States is still highly dependent on fossil sources of energy which tends to disguise the fact that electrified systems can easily be operated as zero-emission systems if only the energy put into their supply systems is changed to renewable sources. It is obvious that "as the share of fossil

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[18] http://www.jimhadams.com/eco/UKEnergyMix2004.pdf Accessed July 2, 2010
[19] http://www.eia.doe.gov/aer/pecss_diagram.html Accessed July 2, 2010
[20] http://ec.europa.eu/energy/energy_policy/doc/factsheets/mix/mix_fr_en.pdf Accessed July 2, 2010
[21] http://ec.europa.eu/energy/energy_policy/doc/factsheets/mix/mix_cz_en.pdf Accessed July 2, 2010

fuels in the electricity generation mix decreases, so increases the advantage of electric trains over diesel trains (Givoni, Brand, & Watkiss, 2009, p. 9).”

Accordingly, Schach, Jehle, and Naumann (2006, p. 14) state that, due to the different mixes of primary energy sources for electricity generation, the CO_2 emissions caused by running a train in the Czech Republic are twelve times higher than in France where a very high share of the electricity generation is achieved by nuclear power plants. The values from Table 34 and Table 35 confirm that differences in CO_2 emissions due to running electrified trains in these countries are huge, however not as large as mentioned above. While electricity generation in France causes 72 grams of CO_2 per kilowatt-hour, this figure is approximately 7.5 times higher in the Czech Republic where it causes 543 grams of CO_2 per kilowatt-hour. This value is comparable to the figure for the United States (519 grams of CO_2 per kilowatt-hour).

To fully use the capabilities of electrified systems to save greenhouse gas emissions, the California High-Speed Rail Authority committed itself to the exclusive use of renewable energy to power the trains that will run on the new high-speed rail system that they plan to implement. This means that the California high-speed rail system would be a true zero-emission system. While the above calculations of CO_2 emissions with respect to current data on energy mixes already show advantages of electrified systems, it is the existing systems like the French TGV system or the Eurostar high-speed system that have to be taken into consideration to recognize the true emission-reduction capabilities of electrified systems. The plans for California show that it is already possible to plan a zero-emission system based on electrified high-speed ground transportation systems. Accordingly, both systems, wheel-on-rail high-speed rail and high-speed maglev, are assigned the highest benefit value in this category (cf. Table 36).

Table 36: Benefit Rating for Pollutant Emissions

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	5	5	5

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.3. Economic Aspects

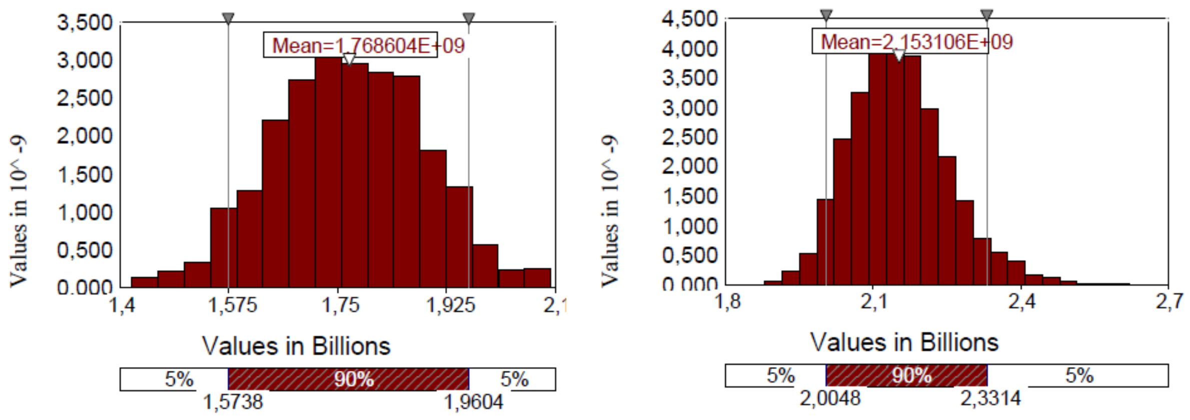
3.3.1. Investment Costs

In order to compare two or more alternative investment options, the concept of life-cycle costs (LCC) needs to be applied. Life-cycle costs encompass all costs that arise from production; construction; operation; upgrading; maintenance, repair, and rehabilitation (MRR); and potential disposal. Because investment require a high volume of expenditures over a comparatively very short stretch of time, they can pose a burden to the implementation of a transportation system as financing becomes increasingly difficult. This is why investment costs are considered in this section as a separate category; other cost types will be dealt with in the following sections.

Capital costs (i.e. the sum of construction costs, land-acquisition costs, and all other one-time costs) for new wheel-on-rail high-speed systems are expected to be significantly greater than capital costs for initiating or improving conventional and high*er*-speed passenger rail services. Based on reported projections, construction costs to initiate new conventional service on existing right-of-way between Cleveland, Columbus, and Cincinnati, Ohio, would be about \$1.4 million per mile (\$0.87 million per kilometer). Similarly, improving existing services to higher speeds could cost about \$1.9 million per mile (\$1.18 million per kilometer) for services in both Pennsylvania and Michigan; \$11.8 million per mile (\$7.33 million per kilometer) for service from New York City to Niagara Falls, NY; and \$15.2 million per mile (\$9.45 million per kilometer) to establish higher speed service from Charlotte, NC, to Washington, DC. As expected, these estimates are lower than projections to develop new wheel-on-rail high-speed services (often referred to as ‘true’ high-speed rail) in Florida and California, which would both require building new dedicated track instead of using existing infrastructure. Based on reported projections, final design and construction for ‘true’ high-speed service between Tampa and Orlando would cost approximately \$36.7 million per mile (\$22.81 million per kilometer) and about $75.5 million per mile ($46.92 million per kilometer) for high-speed service between Los Angeles and Anaheim (GOA, 2010b, pp. 11-12). These numbers are in line with estimations by the National Conference of State Legislatures who expect costs of about $65 million per mile ($40.4 million per kilometer) (Dutton, 2010).

Schach and Naumann (2007, pp. 146-147) carried out cost estimations for the construction costs of the track (not including costs for operation, control systems, and vehicles; not to confuse with capital costs from above) for a hypothetical line section of 100 kilometers (62 miles) of either the wheel-on-rail high-speed system or the Transrapid high-speed maglev system. In Figure 11 the results of this comparison of construction costs are shown. The authors took into account the stochastic variations of the different cost components due to potential differences in the characteristics of the 100-kilometer (62-mile) line segment. The mean costs for the Transrapid maglev system amount to EUR 21.53 million per kilometer of double track and EUR 17.69 million per kilometer of double track for the wheel-on-rail high-speed system. The standard deviation in construction costs for the wheel-on-rail system is EUR 1.0 million per kilometer of double track, while the standard deviation for the Transrapid maglev system is EUR 0.456 million per kilometer of double track. According to Schach and Naumann, this suggests a smaller risk of cost overrun for the Transrapid maglev system. The reasons are mainly seen in the higher ratio of tunnels for the wheel-on-rail system (cf. section 3.2.6 “Need for Construction of Structures (Bridges, Tunnels)”).

Figure 11: Estimated Investment Costs for the ICE Wheel-on-Rail High-Speed System and the Transrapid High-Speed Maglev System



(Source: Schach and Naumann, 2007, p. 147)

Breimeier (2002, pp. 66, 68) gives very similar values to those shown in Figure 11. However, his figures are only valid for flatland alignments where there is no need for costly structures like bridges and tunnels. According to his study, construction costs of EUR 16.4 million per kilometer for wheel-on-rail high-speed rail and EUR 20.4 per kilometer for maglev can be expected. According to the underlying assumption of both authors, it has to be mentioned that these numbers represent very low values that can only be achieved under ideal conditions. For a relative comparison however, these number are still meaningful.

A study by the Federal Railroad Administration (USDOT, 1997) indicated that maglev would have a somewhat (10-20 percent) higher cost per mile than wheel-on-rail high-speed rail. After the publication of the works of Schach et al. and Breimeier this value can be verified as a very good assumption as Schach et al. calculate investment costs for maglev to be 22 percent higher than those for wheel-on-rail while the same figure according to Breimeier is 24 percent. Concerns of Vuchic and Casello (2002, p. 43) that the investment costs of maglev might be about two times greater than those for wheel-on-rail high-speed rail are not supported by these studies. These concerns were based on earlier short-haul studies for the United States that arguably did not, by their characteristics, represent very suitable market segments for maglev so that the cost comparison based on these lines becomes overly unfavorable towards the maglev system. For the Transrapid maglev project that was supposed to connect Munich's airport with the central rail station in the city center of Munich, construction costs were also estimated to be approximately twice as high as for a wheel-on-rail high-speed track. On this short-haul alignment whose environment is partially very densely populated, however, an unusually high number of tunnels would have been necessary. This increases construction costs significantly and makes these numbers unrepresentative for an average track alignment (Schach, Jehle, & Naumann, 2006, pp. 269-270). The general tendency seems to be that the maglev system appears less preferable in terms of investment costs for short-haul alignments.

Construction costs of those HSGT projects that have been implemented are higher than those numbers by Schach et al. and Breimeier from above. Especially the new-constructed wheel-on-rail high-speed track between Cologne and Frankfurt in Germany has been criticized for its costs that exceeded the estimates. The investment costs of the 177-kilometer-long line (110 miles) were EUR 6 billion (Schach, Jehle, & Naumann, 2006, p. 79) which translates to EUR 33.9 million per kilometer. López-Pita, Teixeira, Casas, Bachiller, and Ferreira (2008) say that the median costs for wheel-on-rail high-speed lines in Europe are between $ 13 million and $ 40 million (i.e. between EUR 8.8 million and EUR 27.2 million ($1 = EUR 1.47; 2008 average)) per track kilometer, depending on the function of the line. Assuming that the costs for the Cologne-Frankfurt line are among the more expensive projects, those figures coincide pretty well. The above mentioned estimated costs for the proposed high-speed rail systems in Florida (approximately $36.7 million per mile – $22.81 million per kilometer) and Californian (approximately $75.5 million per mile – $46.92 million per kilometer) also coincide well when considering that these are capital costs as opposed to pure construction costs.

For comparison, the estimated investment costs for a proposed track for the Japanese MLX01 maglev between Tokyo and Osaka (distance approximately 550 kilometers – 342 miles) are EUR 67 billion. This equals EUR 122 million per kilometer[22] (EUR 196 million per mile) which is, as pointed out in the introduction of this thesis, one major reason why this thesis focuses on a comparison between the Transrapid maglev system and wheel-on-rail systems, leaving the MLX01 maglev system aside.

With the construction of the vehicles for the Shanghai maglev system, the production process for the Transrapid maglev has already been mechanized and automated to a large extent. Other parts like the guideway beams have been standardized reducing their number of types to three (Schwindt, 2004, p. 38). Still Blank, Engel, Hellinger, Hoke, and Nothhaft (2004, p. 78) expect investment costs of wheel-on-rail high-speed systems and high-speed maglev systems to further converge in the future.

The next important part of investments costs are the costs for the vehicles. Witt and Herzberg (2004, p. 97) state that the investment costs for the maglev vehicles are clearly higher than comparable cars for wheel-on-rail on rail high-speed trains. This is, on the one hand, due to not yet existing economies of scale for maglev vehicles and, on the other hand, a higher number of expensive electronic components for the maglev vehicles. Furthermore, the Transrapid's manufacturer mentions it as an advantage that "a single supplier takes on responsibility for planning and design, commissioning and maintenance, as well as training of the operating personnel (Siemens, 2006c)". This can certainly be advantageous in terms of management and organization. It can, however, also mean that the organization which is responsible for operating and maintaining the facilities becomes more dependent upon a "single supplier". As such, one could see

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[22] http://www.faz.net/s/Rub163D8A6908014952B0FB3DB178F372D4/Doc~EF43F9B10434D4980BA3F045181BA1D69~ATpl~Ecommon~Sspezial.html Accessed July 14, 2010

certain disadvantages for the operator in negotiating good deals for additional services. This issue is, however, not necessarily exclusive to the maglev system. An operator of a wheel-on-rail high-speed system will not be less dependent on a certain train manufacturer. Even though there are, as opposed to the maglev system, multiple wheel-on-rail high-speed train manufacturers in the market, hardly any parts from one manufacturer can be used on the system of another manufacturer. Since there will be competition between all kinds of high-speed ground transportation systems, it is highly unlikely that neither the maglev manufacturer nor a wheel-on-rail high-speed rail manufacturer will be able to take advantage from a lack of direct competition.

The actual costs for the maglev vehicles are, due to the lack of enough implemented projects, hard to determine. Schach, Jehle, and Naumann (2006, pp. 289-191) estimate a Transrapid high-speed maglev train to be approximately EUR 42 million, about twice as expensive as a ICE 3 wheel-on-rail high-speed train with a similar number of seats, which costs approximately EUR 20 million. The authors and the manufacturer (Transrapid International, 2006, p. 14) say that the figure for the Transrapid maglev should be lowered since approximately 30 percent fewer vehicles are necessary to reach the same transportation capacity due to the higher achievable operation speeds of the maglev system (the train needs less time to travel back and forth so that fewer trains are necessary to operate with the same frequency).

In sum, the investment costs for the track are somewhat higher for the high-speed maglev system (in the range of 20-30 percent) whereas the purchase costs for the maglev vehicles are estimated to be about twice as high as those for wheel-on-rail high-speed trains. This leads to the assignment of the benefit values in Table 37.

Table 37: Benefit Rating for Investment Costs

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	4	2	2

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.3.2. Maintenance, Repair, and Rehabilitation Costs

Deterioration of the installations of a high-speed ground transportation system requires performing a series of maintenance operations in order to reach an acceptable level of operability. According to López-Pita , Teixeira, Casas, Bachiller, and Ferreira (2008, p. 13) the following elements can be involved in the maintenance of a railway line: the track (i.e. rails, sleepers, fastenings, railpads, ballast); switches and crossings; support structure layers (i.e. subballast, form layer, soil layers); structures like bridges and tunnels; signaling installations; telecommunications installations; catenary; energy supply of the electric line. The study, which these components are drawn from, focused on the wheel-on-rail high-speed system. It is obvious that costs that arise from the maintenance of these systems will be significantly lower for the high-speed maglev system because some of the wheel-on-rail system’s parts that require regular maintenance (e.g. the overhead catenary) simply do not exist on the maglev system. Other parts like most track components are wear-free due to the non-contact support, guidance and propulsion of the Transrapid maglev (cf. section 3.1.4 “Wear and Degradation”).

The study of López-Pita, Teixeira, Casas, Bachiller, and Ferreira (2008, p. 17), which was conducted on a representative selection of European wheel-on-rail high-speed lines, suggests that maintenance costs of the wheel-on-rail system are distributed among its subsystems as follows: 45-55 percent for the track; 3-5 percent for bridges and tunnels; 20-25 percent for the catenary and power supply; and 17-22 percent for signaling and telecommunications. Based on the observation and analysis of the maintenance costs of the Paris-Lyon wheel-on-rail high-speed line, it was calculated that the average cost per kilometer of track was approximately 55 percent of the maintenance cost of a conventional wheel-on-rail track with equivalent traffic. This is due to three reasons: 1) The uniformity of the high-speed rail (i.e. the TGV) rolling stock on the line; 2) the lower axle charge of these high-speed trains; and 3) the strict quality conditions imposed during the construction of the line (López-Pita, Teixeira, Casas, Bachiller, & Ferreira, 2008, p. 17).

Since one important advantage of the wheel-on-rail high-speed system is the fact that it can allow freight trains to be operated on the same track (cf. section 3.3.6 "Ability to Use Existing Railway Tracks"), it is important to consider what consequences such mixed operations would have in terms of maintenance costs. Such estimations have been performed for the new high-speed line between Barcelona (Spain) and Perpignan (France) that is slated for mixed traffic. With the addition of freight trains to the line, maintenance costs for the track will be 27% higher, mostly due to the increase of rail grinding and tamping needs. Maintenance costs for other track elements like bridges and tunnels, catenary and power supply systems, and signaling and telecommunications systems, are not expected to change significantly. According to the share of track maintenance costs among the overall maintenance cost, an increase of approximately 11% in overall maintenance costs would be caused by the addition of freight traffic (López-Pita, Teixeira, Casas, Bachiller, & Ferreira, 2008, pp. 17-18).

The total maintenance costs per kilometer of a high-speed line (with exclusive high-speed passenger train usage of approximately 100 trains per track per day) have been determined to be EUR 38,600 per year (López-Pita, Teixeira, Casas, Bachiller, & Ferreira, 2008, p. 19). The authors state, however, that they were, for confidential reasons, not allowed to disclose from which system they drew the data. Due to the high number of trains per day, however, it is probable that this data comes from the French TGV system.

Schach, Jehle, and Naumann (2006, pp. 138-139) conducted a similar calculation based on data from Loos (Loos, 2003). Even though they assume a significantly lower number of trains per day (i.e. twelve trains per day), they calculate the almost exact same total maintenance cost per kilometer per year of EUR 38,763. The fact that they thereby give a higher value per train (i.e. same maintenance cost for fewer trains) is arguably due to the fact that they relate their calculation to another wheel-on-rail system than López-Pita et al. Although interesting, these differences will not be analyzed any further, since the quintessential question is only how these values compare to the maintenance costs of the high-speed maglev system. Based on data from Loos (Loos, 2003), Schach et. al. (2006, pp. 138-139) calculate maintenance costs for the Transrapid high-speed system to be EUR 12,264 per kilometer per year (also assuming twelve trains per day) and, thus, only a third as high as maintenance costs for the wheel-on-rail system. Breimeier (2002, p. 71) agrees that maintenance costs are higher for the wheel-on-rail high-speed system than for the high-speed maglev system. He calculates the wheel-on-rail system's maintenance costs, however, to be only 70 percent higher than those for the maglev system (as opposed to the above 200 percent). Another important property is that the track maintenance costs increase with operating speed on the wheel-on-rail system. For the Transrapid maglev system, the guideway maintenance costs are independent of operating speed.

Vuchic and Casello (2002, p. 43), however, are concerned that the maintenance of the maglev system might be very sophisticated due to the very complex instrumentation on the guideway and on the trains. These concerns are correlated to Breimeier's suspicions that the maglev's guideway might, even in the absence of physical contact in operation, still require costly maintenance work (cf. section 3.1.4 "Wear and Degradation") in case components fail for other reasons than wear. While it was shown above that the Transrapid maglev system has in general significantly lower maintenance costs, it still has to be considered that failures of the electromagnetic components can cause high costs. Therefore, the difference in the benefit rating for the two HSGT systems has to be lowered which leads to the benefit ratings in Table 38.

Table 38: Benefit Rating for Maintenance Costs

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	2	4	4

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.3.3. Operation Costs

Operation costs refer to all costs which do not belong to one-time costs. Accordingly, maintenance costs can also be counted as operation costs. For their complexity, however, they have already been treated in the previous section separately. The remaining operation costs include energy, personnel, insurance, ticketing, marketing and some other minor cost factors.

Because both high-speed ground transportation systems are fed by electric energy, the energy costs almost solely depend on their respective amount of energy consumption. As it has been pointed out is section 3.2.2 “Energy Consumption”, the Transrapid maglev has a lower energy consumption when both systems are operated with a maximum speed of 300 km/h (186 mph). If the maglev system is, however, operated at 450 km/h (280 mph), the level of its energy consumption exceeds that of the wheel-on-rail high-speed train at 300 km/h (186 mph).

Different authors (Witt & Herzberg, 2004, p. 96) (Breimeier, 2002, p. 72) state that personnel costs of the maglev system are expected to be lower. If the maglev is operated with higher travel speeds, less vehicles are necessary to achieve the same transportation capacity, which leads to a reduction of operation costs (Siemens, 2006b, p. 11) as a smaller vehicle fleet requires fewer operating and maintenance personnel (cf.

section 3.3.1 “Investment Costs”). Another important fact is, that the Transrapid maglev has a fully automated operation and therefore does not require a driver on the train (Transrapid International, 2006, p. 14).

In sum, operation costs of the maglev system are lower than those of the wheel-on-rail system. If the maglev system travels with higher speeds, the share of energy costs among total operation cost increases while other costs like personnel costs decrease.

It is also interesting to point out that every HSGT system has its individual cost-optimal speed. While some costs like investment costs and personnel cost decrease with increasing speeds (less trains and thereby less personnel is needed), other costs like energy costs and maintenance cost increase with increasing speeds (maintenance costs are, however, only dependent upon travel speed for the wheel-on-rail high-speed system) (Breimeier, 2002, pp. 33-34). An optimization which considers all speed-dependent cost factor leads to a certain optimal speed where costs are the lowest. This cost-optimal speed is higher for the maglev system than for the wheel-on-rail system.

A study by Witt and Herzberg (2004, p. 102) tried to determine a break-even point at which overall system costs (i.e. the combination of investment costs, maintenance costs, and other operation costs) are approximately the same for both HSGT systems. Due to the higher investment costs of the maglev system, overall costs are higher for the maglev system at first until the cost savings, which correspond to lower maintenance costs and operation costs, balance out the higher investment costs. Witt and Herzberg estimate that this break-even point will be reached after 30 years of operation according to the current state of the art. They argue that the break-even point will probably be reached earlier (they estimate 15 years) for future systems due to the higher development and cost savings potential of the maglev system (cf. section 3.6.3 “Potential for Further Development”).

As described above, the evaluation of operation costs leads to the assignments of benefit values shown in Table 39.

Table 39: Benefit Rating for Maintenance Costs

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	3	4	4

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.3.4. Ridership Generation

The number of passengers attracted to a transportation system (i.e. its ridership) depends on travel fare, travel time, frequency, comfort, punctuality, accessibility to stations, and integration with other modes of transportation. Based on a joint gravity model which uses the generalized cost of each of the available mode of transportation together with a modal split model (logit model), the traffic on a certain transportation system can be calculated dependent on the above parameters (Guirao, 2005, p. 114). For example, it is one the most basic laws of transportation that decreasing the travel time results in an increased ridership just as does decreasing travel fares.

Some of the above factors do not differ very much between the two HSGT systems (i.e. comfort, cf. section 3.4.3 “Comfort”). Others do not directly depend on the type of HSGT system, but on operational characteristics that can be chosen independent of the train technology (i.e. frequency, cf. section 3.4.2 “Arrival Frequency”). Possible differences in ridership are mainly dependent on travel time, travel fares, and system integration.

The various European high-speed rail systems have proved the potential of HSGT systems to attract ridership. Even in cases where railroad connections already existed between given origin-destination pairs, HSGT has increased ridership. Between Madrid and Seville, for instance, train service already existed prior to the inauguration of the Madrid-Seville high-speed line in 1992. It had a market share of 13 percent in 1990. Since the inauguration of the high-speed line, the overall number of passengers has been continuously growing. In 2000, high-speed rail had a market share of 41 percent. While part of the ridership is comprised of former riders of other modes, the high-speed line also induced traffic as it offered travel opportunities that did not exist before. For example, it became feasible for employees to commute very long daily distances, resulting in the term ‘high-speed commuter’. In the particular case of the Madrid-Ciudad Real city pair on the Madrid-Seville line, this impact on mobility has had some very important local territorial implications (Guirao, 2005, pp. 113-115).

The Spanish high-speed rail experience also illustrates the combined effects of travel time, travel fare, and frequency. Due to the restructuring of existing train services which occurred along with the inauguration of the Madrid-Seville high-speed line, some connections (e.g. Madrid-Huelva and Madrid-Cádiz) showed a decline in ridership. On the connection between Madrid and Huelva, which partially uses the Madrid-Seville high-speed line, the underlying changes had been a reduction in frequency of direct services from 42 to 14 services per week and a fare increase of 35 percent. A travel time reduction of 41 percent was the only simultaneous positive impact that could not fully outweigh the negative impacts (Guirao, 2005, p. 114).

As explained in section 3.5.8, the integration of the HSGT systems into the existing transportation infrastructure does not differ significantly between both systems except for the integration with conventional rail services (e.g. regional trains, commuter trains) where the wheel-on-rail high-speed system has the advantage. Also, an interconnected high-speed system can be achieved more easily for the wheel-on-rail high-speed system (cf. section 3.5.7 “Ability to Create a Connected High-Speed Ground Transportation Network”). On the other hand, the high-speed maglev system benefits from its lower travel times, especially if it is assumed to travel with maximum speeds of 450 km/h (280 mph) (cf. section 3.4.1 “Travel Time”). Travel fares are assumed to be approximately equal between both HSGT systems (cf. section 3.4.4 “Travel Fare”).

Summarizing the various influences, the following benefit values for ridership generation (cf. Table 40) have been determined.

Table 40: Benefit Rating for Ridership Generation

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	4	4	5

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.3.5. Chances to Acquire Grants

The implementation of high-speed rail projects is costly and requires substantial up-front public investments (GOA, 2010a, p. 1). In other countries with high-speed intercity passenger rail systems (e.g. France, Japan, and Spain), the government generally funded the majority of the up-front costs of high-speed rail lines (GOA, 2010a, p. 3). This illustrates that the chances of a high-speed ground transportation system to acquire public grants are essential for the success of its implementation. The enormous importance of such funding can be seen in the award of $8 billion from the American Recovery and Reinvestment Act (ARRA) that elevated high-speed ground transportation projects to reach more professional discussion.

The ARRA funds impose a set of requirements that need to be fulfilled in order to be eligible for the funding. Future grant programs can be expected to have similar requirements. Among the ARRA requirements that have been discussed the most is the deadline that ARRA funds be spent by Sept. 30, 2017 (Dutton, 2010). This requirement might be tough for those ‘true’ high-speed rail projects, which this thesis is focusing on. A report by the Government Accountability Office (GOA, 2010b, p. 17), which incorporated interviews with industry stakeholders, states that “design, testing, and production of new passenger rail cars can take anywhere from almost 2.5 years to almost

9 years." This means that for more extensive and time-consuming projects the time frame can be challenging as only seven years are left until ARRA funds must have been spent. On the other hand, it has been proven that, if necessary or desired, even the most demanding projects can be implemented very quickly. The Shanghai maglev system, for instance, started commercial operation in December 2003, less than three years after its construction began in March 2001.

Another requirement of ARRA funding is that the money can only be spent in the United States. While such a requirement is logical as it was the very reason for passing ARRA to support the American economy, it is not possible for either high-speed ground transportation system to have 100 percent of all parts manufactured in the United States (GOA, 2010b, p. 20). Both high-speed ground transportation systems will surely require some special parts. For various reasons, it might be unreasonable to force them to be produced in the United States. For example, it might be disproportionally expensive to set up production facilities for parts of which only a very low number is required. Still, major portions of planning, construction, and production processes can be achieved within the United States. This is equally true for both high-speed ground transportation systems.

Other chances to acquire funds are state bonds or public-private-partnerships. California voters, for instance, have already authorized in a 2008 ballot initiative the issuance of $9 billion of municipal bonds. The complete proposed high-speed system for California is, however, estimated to cost approximately $40 billion. Therefore, authorities in California (similarly in Florida) are planning to include public-private partnerships into their funding programs(Dutton, 2010). The quintessential question for the private sector will be their confidence in the investments into high-speed ground transportation systems. Thorough economic analyses will determine the chances to establish a profitable investment. If either HSGT system is designed properly for a given market so that a good profit can be expected, private investors will not favor or disfavor either system. Concerning public bonds, which need to be approved by voters, the wheel-on-rail high-speed system might be in an advantaged position since skepticism about the maglev system tends to be a little higher (cf. section 3.6.1 “Societal Acceptance”).

In sum, some ARRA requirements are difficult to fulfill for both HSGT systems. Neither system can be expected to be significantly advantaged over the other by the demands of ARRA grants as well as future grants. In grant initiatives, which involve ballots, the maglev system might be slightly disadvantaged. This leads to the assignment of benefit values as shown in Table 49.

Table 41: Benefit Rating for Chances to Acquire Grants

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	4	3	3

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

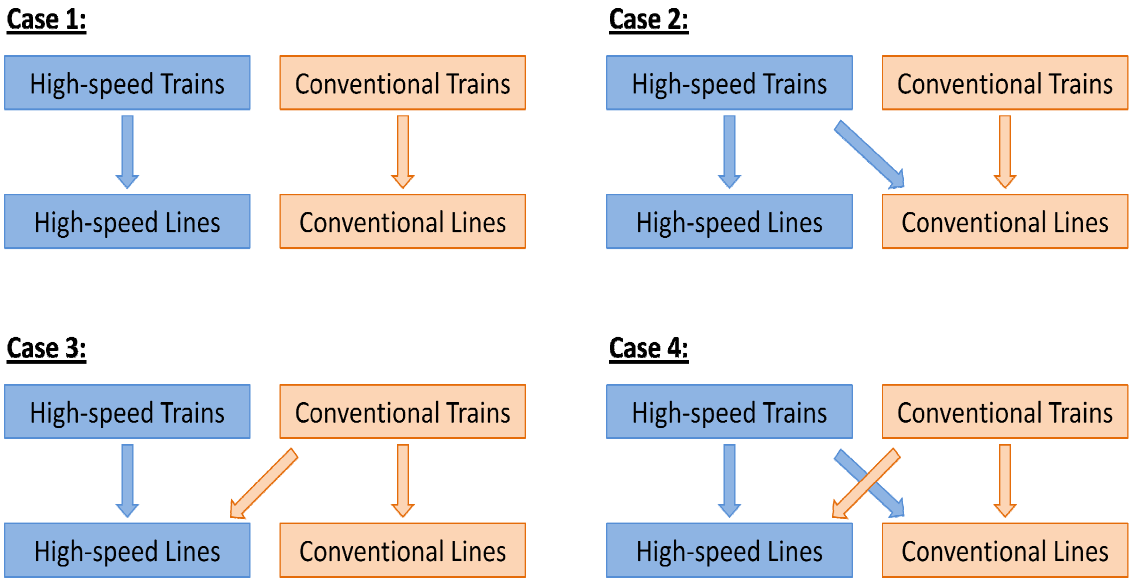
3.3.6. Ability to Use Existing Railway Tracks

The ability of high-speed trains to use existing railroad infrastructure is one of the major points in the current discussion about the implementation of high-speed ground transportation systems. Therefore this section is one of the most extensive in this thesis. Besides the abilities and disabilities that the two HSGT system show in terms of ability to use existing infrastructure, this section also goes one step further and addresses potential problems presented by the use of existing railroad infrastructure.

According to Vuchic and Casello (2002, p. 33) “[wheel-on-rail] high-speed rail has a huge advantage over maglev due to [its] compatibility with existing rail networks.” Although there are technical differences between modern high-speed rail and conventional rail, high-speed trains still travel on the same basic type of infrastructure as today’s freight and passenger trains. Maglev, on the contrary, operates on an entirely different type of guideway.

The following paragraphs analyze to what extent today's high-speed trains in other countries use existing conventional (i.e. non-high-speed) rail infrastructure. Following Guirao (2005, p. 110) there are four cases into which we can group the different ways of operating a network that includes high-speed lines and conventional (i.e. slower) rail lines. Figure 12 illustrates these cases.

Figure 12: Different Cases of Using Rail Infrastructure



In Case 1, high-speed trains never share tracks with conventional trains. This complete segregation of rolling stock can be found today only in Japan on the Shinkansen lines (Vuchic & Casello, 2002, p. 43) that belong to the JR Central and the JR West companies.

In France, high-speed rail lines are exclusively used for high-speed passenger trains (López-Pita, Teixeira, Casas, Bachiller, & Ferreira, 2008, p. 14). High-speed trains can, however, also run on conventional lines (Guirao, 2005, p. 110). Accordingly, the French train network is considered to be Case 2. The highest share of the network, however, is operated separately, which corresponds to Case 1. A very similar situation can be found on the newest German high-speed line between Cologne and Frankfurt. Here, high-speed trains only use conventional lines on the last few miles that connect the newly constructed high-speed line with the train stations in the city centers (Case 2). For the major part of the distance, however, high-speed trains run exclusively on the new high-speed rail tracks where no other trains are operated (Case 1).

The Spanish rail network corresponds to Case 3. There are a few types of trains that can use the high-speed lines on their route (e.g. the Talgo 200). High-speed trains, however, have never been used on the conventional network (Guirao, 2005, p. 110), which is basically due to the technical incompatibility of conventional and high-speed lines. Conventional lines were traditionally constructed in Iberian gauge (1.668 meters – 5 feet 5⅔ inches) while the newly constructed high-speed lines are standard gauge (1.435 meters – 4 feet 8½ inches). The conventional trains that operate on the Spanish high-speed lines are exclusively lower-speed passenger trains (Guirao, 2005, p. 115) (López-Pita, Teixeira, Casas, Bachiller, & Ferreira, 2008, p. 15). Freight trains are prohibited on the Spanish high-speed network (Guirao, 2005, p. 111). Case 4 can be found in Germany and Italy where high-speed trains run on (upgraded) conventional lines while lower-speed trains also run on high-speed lines over significant portions of the network (Guirao, 2005, p. 110).

As the high-speed maglev system uses a completely different type of guideway, it cannot operate on any conventional rail track. Accordingly, it has been criticized that “an additional guided system like a high-speed maglev system which is not compatible with railway means a further specialization in the transportation market and thereby a limitation of its application opportunities. The implementation of the maglev system can technically be seen as the introduction of a new track gauge (Breimeier, 2002, p. 11).” The wheel-on-rail high-speed system is the only system that can be operated on existing rail infrastructure.

The combined operation of high-speed trains and freight trains on either newly constructed high-speed lines or upgraded freight rail lines, however, can cause problems in many respects. As pointed out in section 3.3.2 “Maintenance, Repair, and Rehabilitation Costs”, high-speed lines on which conventional passenger and freight trains are run in addition to high-speed trains have higher maintenance costs. López-Pita (Approximation to the Compatibility between High-speed Passenger Trains and Traditional Freight Trains, 2000) has shown that the common operation of high-speed passenger trains together with conventional passenger trains and freight trains would cause increases in maintenance costs between 2 and 20 percent, depending upon the number of freight trains and the number of passenger trains. Similar estimations have been performed for the new high-speed line between Barcelona (Spain) and Perpignan (France) that is slated for mixed traffic (cf. section 3.3.2 “Maintenance, Repair, and Rehabilitation Costs”). With the addition of freight trains to the line, maintenance costs for the track will likely be 27 percent higher and overall maintenance cost would increase by approximately 11 percent (López-Pita, Teixeira, Casas, Bachiller, & Ferreira, 2008, pp. 17-18). This means that monetary savings that can be achieved when existing tracks are upgraded instead of constructing new tracks can be partially outweighed by higher maintenance costs that arise because of the combined operation of high-speed trains and conventional trains.

Furthermore, combined operation reduces the capacity of a line significantly as very long headways between conventional trains and high-speed trains are necessary due to the huge differences in operation speeds. Figure 13 shows the time-distance diagrams of a hypothetical 50-kilometer (31-mile) segment of a high-speed line. The left part of the figure depicts exclusive high-speed train operation of this line segment. The headway is chosen as five minutes. Because all trains travel with the same speed (300 km/h – 186 mph), their headways stay constant on the whole segment. The right part of the figure depicts mixed operation with high-speed trains (traveling at 300 km/h – 186 mph) and freight trains (traveling at 100 km/h – 62 mph). In order to ensure the same minimum headway as in the left part of the figure (i.e. five minutes) the second high-speed train (HST 2) cannot enter the line segment earlier than 25 minutes after the freight train entered it. Otherwise, the high-speed train would have to slow down after the freight train in order to maintain the 5-minute headway. As a result the second high-speed train cannot arrive at the end of the line segment any earlier than 40 minutes after the first high-speed train had entered the line segment. On the line segment with exclusive high-speed train operation, the seventh train has already arrived at the end of the segment at this point of time (i.e. after 40 minutes). An option to remedy the capacity problem with mixed operation can is to add an additional track to the main line, which the freight train can use to let the high-speed train pass. Even applying these measures, it is still impossible to reach capacities of rail lines that are exclusively operated with trains of one single speed. Furthermore, the schedules would have to be coordinated with busy commuter and freight lines that ply the route.[23]

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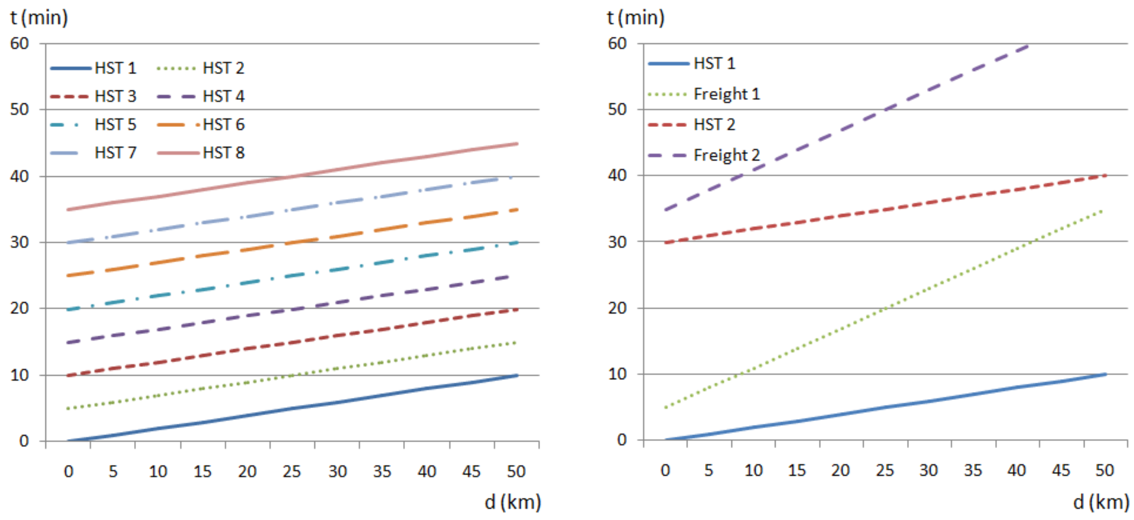
[23] http://www.latimes.com/news/local/politics/la-me-high-speed-rail-20100612,0,5073909.story Accessed June 17, 2010

Figure 13: Capacity of High-Speed Lines in Separate and Mixed Operation



Due to these capacity problems, a full separation of passenger and freight traffic is planned for the proposed HSGT system for the Chinese Beijing-Shanghai corridor in China. On the existing line, passenger trains are restricted to very low speeds to maintain a reasonable capacity (Liu & Deng, 2004, p. 24).

In the United States, most railroad tracks are privately owned (GOA, 2010b, p. 1). This increases the complexity of mixed use of rail lines as access agreements must be negotiated with the private owners. These agreements must specify how costs, such as for maintenance-of-way, are to be shared, or alternatively what access charges must be paid (Zarembski & Cikota, 2008, p. 30). Moreover, it has been reported that freight railroad companies are also concerned about questions of liability coverage for passenger rail providers operating on their tracks. This is a major barrier for host railroads as they see a risk of getting involved in substantial liability claims in case of an accident involving a passenger train on their tracks, even if the freight railroad was not at fault (GOA, 2010a, p. 4).

The introduction of double-stack container transportation on railroads has made freight transportation significantly more economical. Today, double-stack container transportation accounts for almost 70 percent of intermodal freight transport shipments in the United States. All lines, on which containers are transported double-stacked, are diesel-operated and have no overhead catenary. This is due to the fact that railcars carrying double-stacked containers have too high a clearance to fit underneath the overhead catenary. There are only few examples worldwide that combine electrification and double-stack container transportation. In China, containers which have lower heights (8 feet – 2.44 meters) than ISO standard containers (8 feet 6 inches – 2.59 meters or 9 feet 6 inches – 2.89 meters) are used in double-stack operation under catenary. From India, it is reported that freight-only corridors are being constructed with a particularly high overhead catenary of 7.45 meters (24.44 feet) above the rail, which is high enough to run freight cars with double-stacked containers underneath it.[24] While solutions for combining electrification with double-stack container transportation exist, an overhead catenary at the standard height usually precludes double-stack operation.

It has also been argued that in the western United States, where cities and towns are newer and have in the last 50 years grown along highway corridors rather than along railroad corridors, the use of existing railroad infrastructure would disadvantage the accessibility of the high-speed system. Instead, representatives of the Rocky Mountain Railroad Authority, which is considering implementing high-speed ground transportation in Colorado, recommended a new high-speed ground transportation system on new tracks along the interstate corridors as this would connect the population centers much better. Upgrading freight railroad tracks or building new tracks parallel to freight rail corridors would be cheaper in terms of capital costs. According to the Rocky Mountain Railroad Authority, however, such lines are suspected to be less profitable and ‘true’ high-speed

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[24] http://www.venix.eu/intermodal-freight?start=3 Accessed July 15, 2010

rail is not feasible when tracks are shared with freight trains due to the limited compatibility of the two systems.[25]

According to the Federal Railroad Authority's High Speed Passenger Rail Safety Strategy, it is also considered 'general best practice' to operate passenger trains with speeds exceeding 150 mph (241 km/h) on a dedicated right-of-way, i.e. on a railroad track which is reserved for the exclusive use of high-speed passenger trains (GOA, 2010b, p. 14). The plans of the California High-Speed Rail Authority are also based on an entirely new system, i.e. a system with dedicated right-of-way (Schwieterman, 2007, p. 17). The only existing high-speed passenger rail service in the U.S. (i.e. the Acela Express in the Northeast Corridor) runs on upgraded existing freight tracks. Many of the problems of this service are directly related to the use of existing tracks.

In the future, there will surely be agencies that decide to implement new systems and agencies that decide to accept the abovementioned limitations in order to save investment costs and base their passenger rail system on existing freight lines. Besides all the technical, economic, and operational aspects involved, these decisions will arguably be very political. The above limitations in using existing freight lines should be considered in these decisions to the full extent. The aim of this section is, however, not to rate the importance of the capability to use existing infrastructure (cf. chapter 0), but the analysis of the purely technical capabilities. In sum, maglev trains can never use existing rail tracks. Wheel-on-rail high-speed trains can do so in a technical sense. Especially in urbanized areas where trains cannot run very fast and where the acquisition of new right-of-way is expensive or impossible, the ability to use existing railroad tracks can be advantageous. The French TGV, for example uses conventional railroad lines with speeds up to 220 km/h to connect with many city-center stations. Considering the wheel-on-rail

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[25] http://coloradoindependent.com/50016/study-puts-colorado-high-speed-passenger-rail-price-tag-at-22-billion Accessed July 15, 2010

system’s general capability of using existing railroad tracks and all the limitations that apply in doing so, the benefit values in Table 41 have been determined.

Table 42: Benefit Rating for Ability to Use Existing Railroad Tracks

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	3	1	1

1 = Minimum Benefit Value;   5 = Maximum Benefit Value

3.4. Aspects of User Friendliness

3.4.1. Travel Time

According to Vuchic and Casello (2002, p. 34), “one of the goals in building HSR systems has been to increase the domain in which rail is the superior mode not only in convenience but also in speed or travel time.” Therefore, a short travel time is one of the main characteristics determining the quality of a high-speed ground transportation system. In general, travel time is dependent upon travel speed (cf. section 3.1.3 “Travel Speed”), acceleration (cf. section 3.1.1 “Acceleration”), braking characteristics (cf. section 3.1.2 “Braking Performance”), dwell times at stations (cf. section 3.5.3 “Dwell Time at Stations”), the achievable speeds in urbanized areas (cf. section 3.5.5 “Achievable Speeds in Urbanized Areas”) and distance between stations (cf. section 3.5.6 “Suitability for Varying Distances between Stations”). It is essential that the influences of all these parameters are considered to achieve a meaningful comparison of travel times.

Vuchic and Casello elaborate on travel times quite extensively. They argue that “increases in maximum speed have decreasing marginal gains in travel time savings (Vuchic & Casello, 2002, p. 35).” They base this statement on the fact that for a trip of a given distance, an increase in maximum speed in the higher speed ranges has a lower effect on decreasing travel times than the same increase (in absolute numbers) in speed in lower speed ranges. They state as an example that an increase of the maximum speed from 200 km/h (124 mph) to 250 km/h (155 mph) saves 9.7 minutes on a distance of 250 kilometers (155 miles). An increase from 400 km/h (248 mph) to 450 km/h (280 mph) only saves 3.9 minutes on the same distance. Exactly this effect could be observed on the Madrid-Ciudad Real-segment of the Madrid-Seville high-speed line in Spain. On this line segment, part of the 300 km/h-fast (186 mph) AVE trains had been replaced by other, lower-power trains with a maximum speed of 250 km/h (155 mph) at the beginning of 2005. Still, the travel time on this 171 kilometers-long (106 miles) line segment has remained almost the same (Guirao, 2005, p. 111). These relationships, however, are only true for comparisons among the same transportation system where the maximum speed is the only parameter being changed with acceleration, braking rate, dwell times at stations and all other parameters kept constant.

In a fair comparison between two different transportation systems, all the travel-time-relevant parameters that are different between the two compared systems have to be taken into account, i.e. besides maximum speeds also acceleration, braking performance, achievable speeds in urbanized areas etc. Such a calculation has been conducted for the 1,462-kilomter-long (909 miles) proposed alignment of the Beijing-Shanghai corridor by Liu and Deng (2004, p. 25) (62 percent of the distance on a tangent; 38 percent of the distance along curved alignment). They calculate theoretical travel times (i.e. for unconstrained alignment, not taking into account any speed reductions in urbanized areas) of 3.5 hours for maglev and 5 hours for wheel-on-rail high-speed rail. They base these estimations on assumed maximum travel speeds of 450 km/h (280 mph) and 300 km/h (186 mph) and acceleration rates of 1.0 m/s^2 and 0.4 m/s^2 for maglev and wheel-on-rail high-speed rail, respectively. These figures include dwell times at stations. Modifying these values based upon assumed speed reduction in sections with constrained alignments, they estimate that travel times would be approximately 4 hours for maglev and 8 hours for wheel-on-rail high-speed rail. Based on the results of other sections of this thesis (e.g. section 3.1.7 “Flexibility in Track Alignment” and section 3.5.5 “Achievable Speeds in Urbanized Areas”) it has to be agreed that increases in travel times due to constrained alignment will generally be significantly greater for wheel-on-rail high-speed rail than for high-speed maglev. Liu and Deng’s values, where the overall travel time of wheel-on-rail high-speed rail is twice as high as the maglev’s travel time, however, seems to overestimate the differences in travel-time increases. Because alignment constraints also increase the travel time for the maglev system, an overall travel time of 5 hours for the maglev (and 8 hours for wheel-on-rail high-speed rail) appears more realistic for the 1,462-kilomter long (909 miles) proposed alignment.

A similar comparison conducted for a hypothetical 100-kilometer (62 miles) alignment by Breimeier (2002, p. 18) does not appear meaningful because it is solely based on different maximum speeds neglecting differences in all other parameters. Sequentially, he shows that differences in travel time between wheel-on-rail high-speed rail travelling at 300 km/h (186 mph) and high-speed maglev traveling at 400 km/h (249 mph) were only marginal.

In sum, the maglev system has a significantly better performance in terms of travel time than the wheel-on-rail high-speed system. Even for the case in which the maglev system travels with the same maximum speed as the wheel-on-rail system, it performs better in terms of travel time due to its higher acceleration and braking rates and its higher achievable speeds in areas with a constrained alignment. Table 43 shows the corresponding benefit values.

Table 43: Benefit Rating for Travel Time

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	3	4	5

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.4.2. Arrival Frequency

The arrival frequency is an important measure for determining ridership. A higher arrival frequency will have positive impact on ridership generation as well as customer satisfaction. Through a higher arrival frequency more spontaneous travelers are attracted because they do not necessarily have to plan their trip way in advance. Instead, they can just enter a train station anytime knowing that it will not take long until the next train arrives.

The actual arrival frequency on either of the two train systems is a measure that will be defined through the economic optimization of the overall system operation. Both systems have a minimum headway (cf. section 3.5.1 “Capacity”) that determines a minimum frequency that each system can achieve. These minimum headways are, however, ten minutes or even lower, which represent frequencies that are usually not applied in the long-haul transportation market. Therefore, the arrival frequencies in daily operation are almost independent of the high-speed ground transportation system. Both systems offer the ability to operate with any frequency that is determined to be optimal in terms of overall system operations optimization. That is why both systems, for any assumed maximum travel speed, are assigned the maximum benefit value in terms of arrival frequency in Table 44.

Table 44: Benefit Rating for Arrival Frequency

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	5	5	5

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.4.3. Comfort

The ridership comfort of a transportation system is dependent on a number of objective parameters as well as many parameters that underlie subjective impressions. The objective parameters include ride quality (e.g. vibration, accelerations, and centrifugal forces), seat spacing, air-conditioning, noise, entertainment equipment and facilities for communication. The more subjectively perceived parameters include interior design, choice of materials and colors, lightning etc.

By definition, the more objective comfort parameters do not differ very much among different transportation systems. Instead, these parameters are used as input parameters to determine other system characteristics. For instance, maximum lateral accelerations are predefined based upon ridership comfort. Then, these acceleration values are used to determine other values like minimum curve radii etc. (cf. section 3.1.7 “Flexibility in Track Alignment”). Therefore, the difference in terms of ridership comfort between the different high-speed ground transportation systems does by definition not vary significantly.

Both HSGT systems share a number of considerable comfort advantages over airplanes. As both systems are surface transportation system there is no take-off which many travelers experience as stressful. Furthermore, travelers can use more appliances than on an airplane. They can make calls with their cell phones and use power plug-ins, which allow them to use their laptop computers without time limits by battery runtimes.

On modern trains, the arrangement of the seats can be modified easily. Especially the seating pitch can be changed quite quickly. For a fair comparison, however, the same values have to be used, which the other categories of comparison were based on. These values are all based on the respective lower travel class on each train system, i.e. those classes that make up the greatest share of seats on each train.

On the German ICE wheel-on-rail high-speed trains, seat widths are approximately 0.55 meters (1.80 feet). On the Spanish AVE one double seat measures 1.075 meters (3.52 feet) in width (i.e. one seat has a width of approximately 0.54 meters (1.77 feet) (Siemens, 2002). The Japanese Shinkansen trains have wider cars and therefore allow for 5 seats in one row, which have widths between 0.44 meters (1.44 feet) and 0.46 meters (1.51 feet)[26]. Maglev cars are even wider (approximately 3.70 meters –

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[26] http://www.jrkyushu.co.jp/shinkansen-name/index_pc.html Accessed on July 12, 2010

12.13 feet) so that 6 seats per row are possible. Such a seating arrangement would allow for seats width of 0.48 meters (1.57 feet) (Schach, Jehle, & Naumann, 2006, p. 146).

Seats on the Japanese Shinkansen trains have a pitch of 1.04 meters (3.41 feet). Seat pitches on the ICE used to be 0.97 meters (3.18 feet), but have been reduced to 0.92 meters (3.02 feet)[27] to increase capacity. The Spanish AVE also has a seat pitch of 0.92 meters (3.02 feet) (Siemens, 2002). The seats of the Transrapid maglev are assumed to be arranged with a seat pitch of only 0.86 meters (2.82 feet). This offers advantages in terms of capacity that have been considered in the corresponding section. In terms of comfort, however, the lower seat pitch is obviously a disadvantage. For comparison, seat pitches on airplanes of United Airlines are between 0.78 meters (2.56 feet) and 0.81 meters (2.65 feet). Those on Air Canada are 0.81 meters (2.65 feet)[28].

As pointed out in section 3.1.6 “Compactness of Train”, it is assumed that for high-speed trains in the United States the wider versions of wheel-on-rail high-speed trains (i.e. approximately 3.25 meters – 10.66 feet) will be used. This can either increase seating space and, thus, seating comfort or transportation capacity. Consistent with the calculations of section 3.1.6 “Compactness of Train” (wider trains will improve weight-per-passenger and length-per-passenger values), it is assumed that wider cars will improve capacity rather than further increase the level of comfort. Consequently, seat widths are assumed to be approximately the same on both systems. Interestingly, the first class vehicles of the Shanghai maglev system use the same seats as the first class wagons of the ICE 3 wheel-on-rail high-speed trains (Lobach & Köb, 2004, p. 53) which illustrates how comparable both train systems are generally in terms of seating comfort.

For the higher assumed seat pitches on the wheel-on-rail system and comparable seat widths, the following benefit values for comfort (cf. Table 45) have been assigned.

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[27] http://www.smavel.com/index.php?aid=723 Accessed on July 12, 2010

[28] http://www.smavel.com/index.php?aid=723 Accessed on July 12, 2010

Table 45: Benefit Rating for Comfort

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	5	4	4

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.4.4. Travel Fare

From October 2003 on, the travel fare on the Shanghai maglev was between \$6 and \$7 (Liu & Deng, 2004, p. 26). As no long-haul maglev system exists yet, this is the only available information about travel fares on a maglev system. Because the Shanghai maglev system is a short-haul airport connection, it is not meaningful to compare its travel fare with those of wheel-on-rail high-speed systems, which cover extensive long-haul networks. Furthermore, travel fares are only to a minor extent dependent on the train technology. Of course, investment costs need to be paid off as well as maintenance and operation costs are expected to be covered as much as possible by travel earnings. The exact travel fares do, however, depend on financial strategies, which do not depend on a certain high-speed system technology.

In sections 3.3.1 “Investment Costs” through 3.3.3 “Operation Costs”, it has been pointed out that the maglev has, in general, higher investment costs than the wheel-on-rail high-speed system, but, on the other hand, lower maintenance and operation costs. Accordingly, there will be a break-even point after which overall costs of the maglev system will be lower than those of the wheel-on-rail system. The time of this break-even point can be altered by the choice of travel fares. If, for instance, travel fares on the Transrapid maglev system are selected higher than those of the wheel-on-rail high-speed system, the break-even point will be reached earlier.

Final travel fares will be determined by more complex economic optimization processes. According to the basic laws of transportation which describe the interdependence of ridership, travel time, and travel fare, section 3.3.4 “Ridership Generation” already evaluated both system in terms of expected ridership. Due to the direct interdependence between travel fares and ridership generation, an assumption of either figure had to be made in order to make a statement about the other. Section 3.3.4 stated that ridership on the maglev system will, due to travel time savings, be higher when travel fares are comparable. In order to be consistent, this section has also assumed that travel fares will be on a similar level, and thus have the same benefit value (cf. Table 46).

Table 46: Benefit Rating for Travel Fare

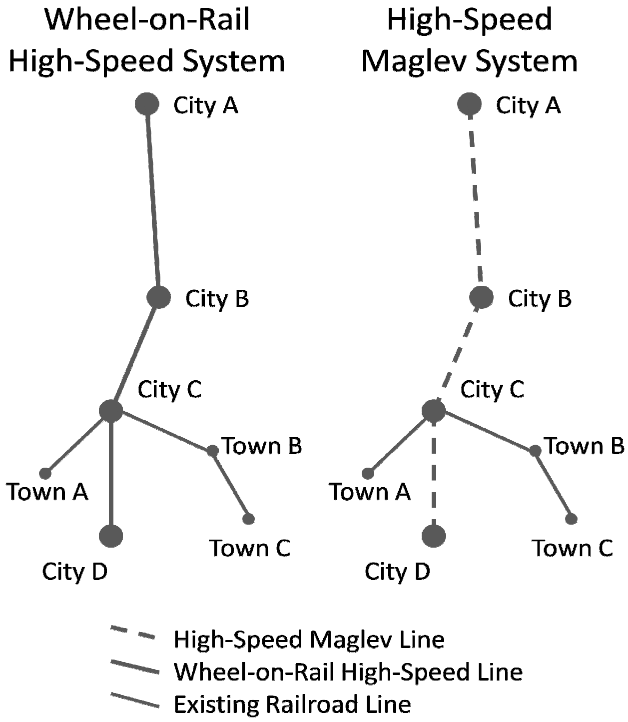
	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	5	5	5

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.4.5. Number of Transfers

As described in section 3.3.6 “Ability to Use Existing Railway Tracks”, the high-speed maglev system can only be operated on dedicated guideways, whereas the wheel-on-rail high-speed system can generally also use existing railroad tracks if related limitations are considered acceptable. One benefit of the capability of using non-high-speed rail tracks is the potential to reduce the number of transfers. Figure 14 illustrates how transfers can be reduced or totally avoided.

Figure 14: Expected Number of Transfers on Different HSGT Systems



Both parts of the figure show the same selection of four cities and three towns. In either part of the figure, the new high-speed ground transportation line connects the four cities. It is assumed that the three towns are already connected to City C by conventional railroads (e.g. freight rail lines). As the maglev high-speed train cannot travel on any existing conventional railroad tracks, a traveler who wants to go from City A to Town B has to switch trains in City C. Through a good integration of the different modes of transportation (e.g. integrated fare structures, coordinated schedules, cf. section 3.5.8 “Integration with Existing Transportation Infrastructure”) this can be achieved without major loss of comfort and time. Ideally, only a very short walk inside an intermodal terminal is necessary to switch from the mainline high-speed maglev train to a regional train or commuter train, which travels on the existing conventional line and connects City C with Towns B and C.

On the wheel-on-rail high-speed system this transfer can be avoided. Operation can be organized in a way that a subset of all daily trains that travel the mainline between the four cities departs from the mainline at City C and travels the rest of its trip on the existing conventional railroad line between City C and Towns B and C. Such an operation, however, also poses limitations. As the conventional railroad line between City C and Towns B and C is not specifically designed for high-speed trains, only a very limited speed can be achieved on this line, even if upgrades have been made to it. Furthermore, operational limitations might apply if the line is owned by a private freight rail company, which is the most common case in the United States. Moreover, the operation on the conventional line is only possible in case it is electrified. An electrification might, however, cause limitations for freight railroad operations on this line (e.g. double-stack container transportation, cf. section 3.3.6 "Ability to Use Existing Railway Tracks"). Train frequency on the secondary line will also be lower as, for traffic demand reasons, the major share of all trains will have to travel the main line. If ways to remedy obstacles and to accept limitations are found, however, the wheel-on-rail high-speed system has the potential to avoid a transfer in City C. According to Vuchic and Casello (2002, p. 43), a reduced number of transfers can often offset the travel time gains achieved by higher speeds.

Because of the higher number of required transfers of the high-speed maglev system and the technical, even though limited, capability of the wheel-on-rail high-speed system to avoid transfers, the following benefit values (cf. Table 47) have been determined. The case with the faster-travelling maglev system is assigned a higher benefit value than the slower-travelling one, since transfers are more tolerable due to travel time savings.

Table 47: Benefit Rating for Number of Transfers

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	4	2	3

1 = Minimum Benefit Value;   5 = Maximum Benefit Value

3.4.6. Service

On-board services are affected in only a limited way by the type of high-speed ground transportation system. Technically both high-speed ground transportation systems are capable of carrying facilities that allow the preparation of food on-board. Traditionally, most railways carried dining cars, which tried to resemble a full-service restaurant as much as possible. Such dining cars were necessary due to long travel times. German ICE trains also carry dining cars even though they have been running at a deficit for many years now. They are, however, considered important to keep those passengers who regularly use them when riding a train as customers of this mode of transportation. Today, it is more common to have food served to the passengers at their seats. As such, only a small facility is necessary to prepare meals, while the extra seating space in a fully-equipped dining car can be saved. This is equally true for both high-speed ground transportation systems. In case, however, a more traditional dining car should be desired, the wheel-on-rail system is advantaged since there is already experience with carrying this type of cars on this train system.

All other on-board services like entertainment and information can be almost equally well offered on either high-speed ground transportation system. Accordingly, the following benefit values (cf. Table 48) are assigned.

Table 48: Benefit Rating for Service

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	5	4	4

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.4.7. Accessibility of Stations

The accessibility of stations is dependent on their location within a city, which determines how many potential customers live close to it and perhaps even more by the station’s connections to local modes of transportation like metro, light-rail, or bus networks. Parking facilities also influence the accessibility of stations.

Accessibility of stations and the optimization of track alignments with respect to travel time can contradict each other. This can be observed on parts of the French high-speed rail network where stations have been newly constructed on greenfields outside of medium-sized cities. Thus, the time needed to travel through the city to reach city-center stations, which almost always require significantly reduced speeds, can be saved. In these cases, transportation planners deemed lower travel times between two major cities more important than an improved accessibility of the high-speed system for the concerned city. Whether such designs will be applied to future high-speed ground transportation systems is less dependent on the applied train technology, but rather on travel demand forecasting analyses that determine which option generates the higher overall ridership.

In older cities of the United States, city-center train stations already exist. As opposed to European cities where central train stations often serve as a hub for local transportation systems like metro, light-rail, or bus networks, city-center train stations in U.S. cities are often less strongly connected to local transportation systems. Due to the existing land use and infrastructure, they still offer the best locations for stops of HSGT systems in most cases. While wheel-on-rail high-speed train can reach these stations on existing railroads tracks, maglev high-speed system can also be connected to these stations as the integration of a maglev system in an urbanized area is generally uncomplicated due the flexible alignment characteristics of the maglev system. Additionally, part of the station's platforms would have to be converted from wheel-on-rail platforms to maglev platforms.

In many newer U.S. cities, for example in the Western states, passenger rail stations do not exist. Here, the crucial question is how easy new stations can be integrated into a given city. As explained in section 3.1.9 "Integration of Stations into Cities", the integration of a maglev station might be somewhat easier due to lower land requirements and the higher flexibility in the alignment of the guideways that connect the new station.

The extent to which a station of either system is connected to the rest of the city is determined by the city's efforts to expand and improve local transportation systems. The success of a high-speed rail system will be highly dependent on these efforts to establish integrated, intermodal transportation connections. How well local agencies advance local transportation system is, however, mainly a political process that is not directly related on the choice of either HSGT system. Because either HSGT system can be perfectly accessible in case local transportation systems are designed to connect to the HSGT station, both systems are assigned the maximum benefit values as shown in Table 49.

Table 49: Benefit Rating for Accessibility of Stations

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	5	5	5

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.4.8. Baggage Transportation

Convenience in transporting Baggage on either high-speed system is mainly dependent upon the interior design of trains as opposed to the train system. For both systems there have been some plans and recent innovations that make baggage transportation easier and more convenient for passengers. For the maglev airport connection in Munich, for example, it was planned that large airline companies could sell their tickets directly at the central rail train station where passenger could also immediately check-in and claim their baggage. The baggage would then be taken directly to the airport so that the passenger would not have to care about it anymore while riding the maglev to the airport (Siemens, 2006b, p. 17). A similar system already exists with the so-called AIRail service. This is an integrated intermodal product from Lufthansa and Deutsch Bahn (Germany's national railroad operator) that offers integrated ticketing and baggage handling for airline passengers that reach their departure airport on certain high-speed rail lines. The trip to the airport by rail is handled like a feeder flight. The customer only has to buy one ticket, check in only once, and claim his or her baggage also only once.

Such services show how well different modes of transportation can be integrated in order to create a seamless, intermodal transportation system. Similarly, other services and facilities that ease baggage transportation can easily be integrated into both systems. As mentioned earlier, there are almost no system characteristics that benefit or disadvantage either system in terms of baggage transportation. As baggage handling is, instead, almost exclusively dependent on the operational characteristics and interior design, both systems are assigned the same benefit values in Table 50.

Table 50: Benefit Rating for Baggage Transportation

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	5	5	5

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.4.9. Image and Attractiveness

Besides technical, operational, and other aspects, transportation systems can be considered more or less attractive for a variety of reasons. Oftentimes transportation systems have a certain image that has developed of time and has since stuck with the transportation system.

Some authors say that the maglev system, due to its more innovate technology, has a higher attractiveness (Witt & Herzberg, 2004, p. 96). Others argue that it is solely the higher travel speeds and shorter travel times that make maglev more attractive (Schach & Naumann, 2007, pp. 141-142). Vuchic and Casello (2002, p. 38) talk about the "strong public appeal" of the maglev system because of its unique features. They also believe that "it is likely that the shape and levitation of Transrapid [maglev] trains would have a good public appeal (2002, p. 44)." They, however, also mention the significant advances high-speed rail has made during the last 25 years. So, "it is in the final consideration difficult to extract any major differences in attractiveness between the two systems." (Vuchic & Casello, 2002, p. 44)

This thesis follows this reasoning and argues that, if no major mistakes are made in operating and marketing either system, both high-speed ground transportation systems are capable of having a very good image and a high attractiveness, with the maglev system having slightly better values as shown in Table 51.

Table 51: Benefit Rating for Image and Attractiveness

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	4	5	5

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.5. Operations

3.5.1. Capacity

The capacity of a rail line is calculated by multiplying the capacity of an individual train, i.e. number of seats, by the number of trains that can travel the line per hour (Liu & Deng, 2004, p. 22). The latter figure is dependent upon the minimum headway between two trains. The transportation capacity of a rail line is one of its most characteristic advantages over other modes of transportation. For comparison, only some 200 persons per hour per meter width of road can be moved with automobiles. With buses 1,500 persons can be moved per hour on the same roadway width and with trains this figure is approximately 9,000. (Smith, 2003, p. 245)

The minimum headway for the Transrapid high-speed maglev system is dependent on distance between power substations and the arrangement of so-called propulsion blocks. In case the substation is equipped with one propulsion block per track, at least one drive control zone must remain free between two trains following each other. In case the substation possesses two propulsion blocks, the following train can enter a drive control zone as soon as the train ahead has left it (Blank, Engel, Hellinger, Hoke, & Nothhaft, 2004, p. 66). Consequently, for no configuration can more than one train be in one substation segment thus determining the minimum headway for the Transrapid maglev system.

It has been reported (Schach, Jehle, & Naumann, 2006, p. 209) that a minimum headway of five minutes would be technically feasible for the maglev system. The manufacturer calls this the ‘theoretical minimum headway’ (Transrapid International, 2001). It has to be questioned, however, whether this is applicable in reality since distances between substations would have to be short in guideway sections where the maglev travels with lower speeds, e.g. near stations. A minimum headway that can surely be achieved is ten minutes. This figure is also proved in commercial operation as the

Shanghai maglev system is designed to allow vehicles to operate at this headway (Siemens, 2006c). For the wheel-on-rail system, headways of three minutes are successfully applied on different routes of the French TGV and the Japanese Shinkansen systems (Liu & Deng, 2004, p. 22).

The Beijing-Shanghai corridor, which Liu and Deng's work focuses on, is arguably among the busiest high-speed ground transportation corridors in the world (Liu & Deng, 2004). Based on an extra-long Japanese Shinkansen train and a 10-section Transrapid maglev (i.e. the maximum number of section according to its manufacturer) they conclude that the capacity of both technologies is not reached in the Beijing–Shanghai Corridor. However, the calculated headway for the Transrapid maglev is much closer to its minimum headway than that of the wheel-on-rail system. As stated above, this corridor is one of the busiest in the world. According to Liu and Deng, capacity is less likely to be a consideration in any other corridors if it is not in the Beijing-Shanghai corridor (Liu & Deng, 2004, p. 26).

Based on technical properties, however, it has been shown that the wheel-on-rail system can reach higher maximum capacities than the high-speed maglev system, which results in the benefit values shown in Table 52.

Table 52: Benefit Rating for Capacity

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	5	4	4

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.5.2. Reliability

Reliability describes the ability of a system to perform its functions in routine circumstances, as well as hostile or unexpected circumstances, with little variation in performance. In case of a power outage, none of the two HSGT systems can be propelled. Because the wheel-on-rail system is supported by a mechanical system (i.e. the wheel-rail interaction) its support can be maintained in case of a power outage. The electromagnetically-based support of the Transrapid maglev system is assured in case of a power outage as well. Because the support and guidance system is fed by on-board batteries (Transrapid International, 2006, p. 5), the train is able to maintain levitation until the next stopping area is reached even in the case of the greatest possible assumed disruption to operations. Just as for the wheel-on-rail system, nothing except the propulsion gets lost in case of a power outage. This property is called ‘safe hovering’ (Lobach & Köb, 2004, p. 58).

Due to its more sophisticated propulsion, guidance and support system the maglev system is considered by some as more vulnerable to adverse environmental conditions. Due to the lack of mechanical contact to the guideway during operation, for instance, the influence of strong winds might be an issue. Corresponding tests have been conducted on the Transrapid Test Facility (TVE) in Germany. According to these tests, cross winds and gusts have little effect on the Transrapid because its active control and guidance system is designed to account for such impacts. Wind velocities of up to 108 km/h (67 mph) have no effect on operation at all. It has also been proved that the vehicle can be operated without difficulty at speeds of up to 350 km/h (220 mph) with wind gusts up to 150 km/h (94 mph)(Transrapid International, 2006, p. 21). Winds of such strengths can have effects on the operation of almost any transportation system. Hence, it cannot be said that the Transrapid maglev system was particularly sensitive to strong winds.

Lightning could be expected to affect the electromagnet-based guidance and support. According to Lobach and Köb (2004, p. 59), however, the Transrapid maglev vehicles fulfill all lightning protection requirements which means that it guarantees the protection of the passengers against a direct strike of lightning. It also protects against damage or destruction of safety-relevant subassemblies due to indirect lightning effects.

It is known that weather conditions can have effects on mechanical friction. As the propulsion of the wheel-on-rail high-speed system is based upon friction, acceleration performance can decrease in adverse weather conditions, e.g. when rails are wet or icy. Rates of deceleration are similarly dependent on such conditions. As modern high-speed trains do, however, receive part of their braking power from non-friction based systems, e.g. eddy-current brakes, deceleration is generally less dependent on weather conditions than acceleration. The rates of acceleration and deceleration of the maglev trains are, by contrast, totally independent of the weather conditions (Siemens, 2006c). Since the start of commercial operation of the Shanghai maglev system in January of 2004, the technical availability of service was 99.9% (Siemens, 2006b, p. 15).

In sum, both HSGT systems have a very high reliability. Disruptions in the power supply basically have the same effect on both systems. Both systems can handle adverse weather conditions very well with only minor limitations. While wet or icy rails decreases acceleration performance of the wheel-on-rail system, strong winds may require a reduction of travel speeds of the high-speed maglev system. Accordingly, both HSGT systems are assigned the same benefit rating with respect to reliability as shown in Table 53.

Table 53: Benefit Rating for Reliability

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	5	5	5

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.5.3. Dwell Time at Stations

The dwell time at a station is mainly dependent upon two parameters. First, the train has to stop long enough to allow passengers to disembark and embark. Secondly, some technical procedures must be completed. For example, a maglev train has, for safety reasons, to be de-levitated and grounded before people can disembark and embark. Because the Transrapid maglev is automatically operated without a driver, safety rules recommended that there be platform edge doors (PEDs) that prevent people from entering the tracks. The operation of such platform edge doors also requires time (approximately six seconds) (Schach, Jehle, & Naumann, 2006, p. 171). So, the overall dwell time at stations is approximately 30 seconds per stop higher for the high-speed maglev system (Breimeier, 2002, p. 17) (Schach, Jehle, & Naumann, 2006, p. 171). To what extent other system properties can outweigh an increased dwell time has been dealt with in section 3.4.1 “Travel Time”. The increased dwell times of the maglev system results in the benefit rating shown in Table 54.

Table 54: Benefit Rating for Dwell Times at Stations

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	4	3	3

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.5.4. Flexibility in Operation

As known from freight rail operations, the ability to quickly couple and uncouple cars in order to reassemble trains increases operational flexibility and economic efficiency. Due to the optimization of such things as aerodynamics and propulsion, modern high-speed trains lack the ability to be altered in configuration. A TGV train, for instance, does not actually consist of individual cars. Bogies are located between two cars rather than at the two ends of each car. While this offers advantages in other categories of comparison, this technology prevents changing the number of units in daily operation. Instead, one train is considered one unit, which is always operated in the same arrangement. As opposed to the TGV, the individual cars of the ICE have their own bogies. The first two generations of the ICE would have allowed changing the number of cars. The third generation of the ICE (i.e. the ICE 3), however, represents a multiple-unit train whose propulsion force is distributed evenly among the whole train. As such, the train does not have locomotives. Each car of the train fulfills some of the functions that were in preceding generations solely fulfilled by locomotives. For the ICE 3, eight cars are considered one unit. No car can be taken out of this unit. The only way to change the number of cars on an ICE 3 train is to couple two eight-car ICE trains together. In daily operation, this offers the chance to split one long sixteen-car train at the last station before the track divergences into two less busy lines, which can then each be travelled by one of the two halves (i.e. eight-car units) of the full train. This operational strategy is widely applied on the German high-speed rail network. Many French TGV trains also offer the capability to be coupled with a second short train of the same type.

A maglev train can consist of two through ten sections, i.e. at least the two end sections plus from zero to eight middle sections. In terms of technical characteristics the middle sections are all the same, which means that their number can technically be decreased or increased. The required procedure to achieve this, however, is not designed to be employed in everyday operation.

In sum, modern wheel-on-rail multiple-unit trains can only be operated as a unit with a fixed number of cars. Two short trains can, however, be coupled together, which can be beneficial for certain operation strategies. The maglev offers the capability to add or reduce individual cars, which is, however, too complicated a procedure to be useful for everyday operation. Accordingly, both HSGT systems are assigned a rather low benefit value for this criterion. The wheel-on-rail system gets a higher value because the coupling of two trains offers at least one option to change the number of cars.

Table 55: Benefit Rating for Dwell Times at Stations

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	3	1	1

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.5.5. Achievable Speeds in Urbanized Areas

As opposed to general travel speeds, the maximum achievable speeds in urbanized areas are very seldom dependent on the technical performance of the train. Instead, the impacts on the residents (e.g. vibration, noise) who reside in these urbanized areas are more determinant.

The level of vibration (cf. section 3.2.9 "Vibration") that a Transrapid high-speed maglev causes when travelling at a distance of 25 meters (82 feet) at a speed of 250 km/h (155 mph), is below the human perception level. At a distance of 50 meters (164 feet), no vibration is noticeable at all. The levels of vibration of wheel-on-rail high-speed trains are significantly higher (they cause, for instance, the same vibration when travelling at 135 km/h (84 mph) as a maglev train at 400 km/h (249 mph)) (Rausch, 2004, p. 25). As such, a high-speed maglev can travel through a densely populated area with speeds of at least 250 km/h (155 mph) without impacting residents in terms of vibrations. For the wheel-on-rail system, speeds have to be significantly lower in order not to emit too high vibrations.

Table 56 summarizes the noise emissions of the two HSGT systems (cf. section 3.2.3 "Noise Emissions") and two roadway vehicles. Note that noise emissions in decibels (dB) are measured on a logarithmic scale, which means that an increase by 10 dB is perceived by the human ear as a doubling of the noise level (i.e. 80 dB is perceived twice as loud as 70 dB).

Table 56: Comparison of Different Transportation-Related Noise Emitters

Sound Pressure	ICE 3 at a Distance of 30.5m and 140 km/h	Transrapid at a Distance of 30.5m and 200 km/h	Pickup Truck at a Distance of 15m and 80 km/h	Medium Truck at a Distance of 15m and 80 km/h
dB (A)	80	80	70	80

(Source: Data from Section 3.2.3 "Noise Emissions" and FHWA[29])

According to Table 56, the noise emission of a Transrapid maglev travelling at a distance of 30.5 meters (100 feet) at 200 km/h (124 mph) is the same as that of a medium-sized truck travelling at a distance of 15 meters (50 feet) at 80 km/h (50 mph). Based upon these numbers, Figure 15 gives an impression of how a Transrapid maglev system could be operated at high speeds in an urbanized area. As shown in the figure, an elevated guideway of the high-speed maglev system could be aligned on the median of an existing arterial-road corridor where roadway vehicles travel at 50 mph (80 km/h) or more. In such a corridor, a Transrapid high-speed maglev could travel with a speed of at least 200 km/h (124 mph) without exceeding the noise level of a medium truck travelling on the arterial road with 80 km/h (50 mph).

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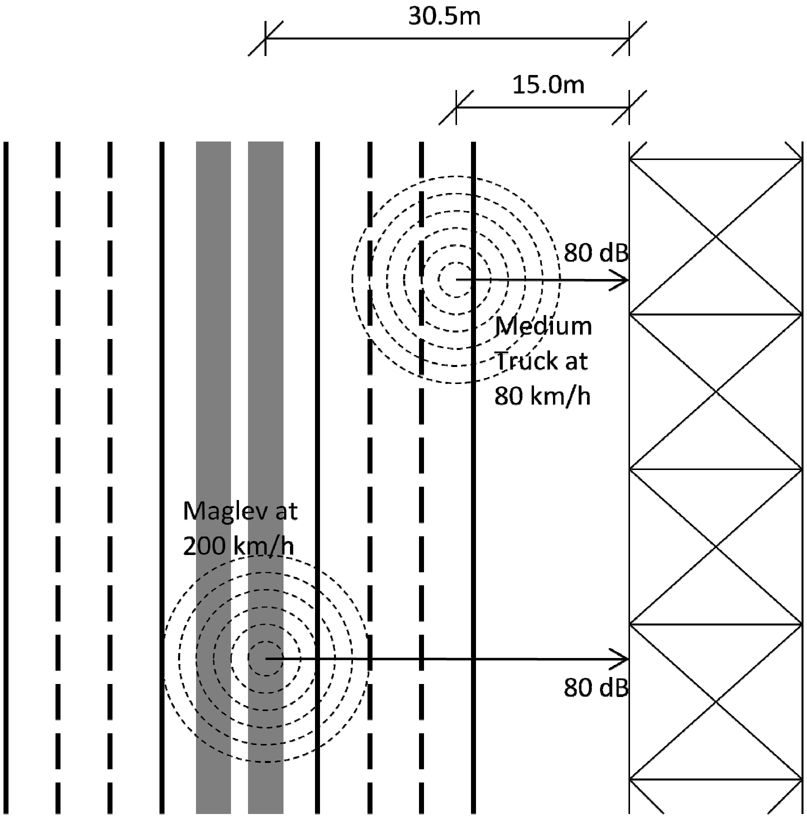
[29] http://www.fhwa.dot.gov/environment/htnoise.htm Accessed July 23, 2010

Figure 15: Possible Alignment for High-Speed Maglev Systems in Urbanized Areas



The Federal Highway Administration (FHWA) mandates that in residential areas a noise level of 70 dB (in commercial areas 75 dB) may not be exceeded more than ten percent of the time. In any city, there are, however, already corridors (in particular along arterial streets) on which these noise levels are higher. On these corridors, the Transrapid maglev system can be easily integrated on an elevated guideway (cf. section 3.1.7 “Flexibility in Track Alignment”).

For an elevated maglev guideway in such a corridor, land would only be consumed for the supporting columns of the guideway. Due to the much lower number of passings of a maglev train as compared to the number of trucks on most arterial roads, even slightly higher noise emissions by the maglev trains would be acceptable. At a travel speed of 250 km/h (155 mph), noise emission at a distance of 30.5 meters (100 feet) would be approximately 83 dB which is by the human ear perceived as somewhat higher than the 80 dB of a medium truck. Schach, Jehle, and Naumann (2006, p. 191) confirm that cruising speeds in urbanized areas can be as high as 250 km/h (155 mph).

A wheel-on-rail high-speed train would cause noise emissions of 80 dB at a speed of approximately 140 km/h (87 mph). The values Liu and Deng (2004, p. 23) estimate, agree with these calculations. Furthermore, the wheel-on-rail high-speed system cannot be as well integrated into a city as the high-speed maglev system because it is not that suitable to be aligned on an elevated guideway. Instead, a wheel-on-rail system would likely run on existing railroad tracks within cities (cf. section 3.3.6 "Ability to Use Existing Railway Tracks"). While this offers cost savings, such an operation can be expected to pose a number of limitations (e.g. limited speeds, operational limitations).

It is also worth mentioning that rail systems in the United States today are affected by limited speeds in urbanized areas due to too high noise levels. For instance, "Amtrak, Metrolink and commuter lines in San Diego County can go up to 125 mph, but because of the corridor's proximity to homes and businesses, the maximum speed is no more than 90 mph[30]." In order to benefit from the high travel speeds of a high-speed ground transportation system as much as possible, it is essential that as high speeds as possible be achieved in urbanized areas without impacting local residents. Following the above explanations, the Transrapid maglev system is assigned a higher benefit value for this category as shown in Table 57.

Table 57: Benefit Rating for Achievable Speeds in Urbanized Areas

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	3	5	5

1 = Minimum Benefit Value;   5 = Maximum Benefit Value

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[30] http://www.latimes.com/news/local/politics/la-me-high-speed-rail-20100612,0,5073909.story Accessed June 17, 2010

3.5.6. Suitability for Varying Distances between Stations

The suitability of a high-speed ground transportation system for varying distances between stations is largely dependent upon its acceleration and braking performance, the energy consumed in these processes, as well as effects on investment costs that arise from a changed spacing between different stations. As pointed out in sections 3.1.1 “Acceleration” and 3.1.2 ”Braking Performance”, the maglev system shows significantly higher acceleration and braking rates, which is why an additional stop on a trip has a lesser impact on overall travel time than an additional stop on the wheel-on-rail high-speed system. The Spanish AVE wheel-on-rail high-speed train, for instance, travels the 625 kilometers (388 miles) between Barcelona and Madrid in 2 hours and 38 minutes, which means an average speed of 237 km/h (147 mph). Any stop between the two termini causes an increase in travel time of at least twelve minutes (Thornton, 2009, p. 1906), which is a multiple of the pure dwell time at the station. This is due to the comparative long time needed for deceleration before the stop and acceleration after the stop. As such, the distance between stations is the single, most important factor determining travel times for the wheel-on-rail high-speed system (Vuchic & Casello, 2002, p. 35) (Schach & Naumann, 2007, pp. 141-142). From a travel time point of view, the Transrapid maglev system has better performance for stations of any distance apart.

Section 3.2.2 “Energy Consumption” showed that the maglev system has usually lower energy consumptions in the higher speed ranges. In the lower speed ranges, however, the maglev system consumes more energy because the energy needed for levitation does not drop with decreasing speeds. As such, the advantages in terms of energy consumption decrease in those cases where the maglev system travels with lower speeds on a higher percentage of a given distance.

Section 3.5.1 “Capacity” described that no more than one maglev train can be in one drive control zone between two power supply substations. This determines the minimum headway for the Transrapid maglev system and infers that the distances between substations have to be smaller on guideway sections where lower speeds are travelled. Accordingly, section 3.3.1 “Investment Costs” explained that the relative difference between construction costs for the maglev system and the wheel-on-rail system increases where station spacings are shorter.

In sum, the maglev system has advantages in terms of achieving shorter travel times for both short and long station spacings. For shorter distances, the maglev system becomes, however, less favorable in terms of energy consumption and investment costs. Therefore, the maglev system is surely superior for larger station spacings. For shorter distances between stations, however, a tradeoff decision between favoring shorter travel times (i.e. the maglev system) or lower costs (i.e. the wheel-on-rail system) has to be made, which tends to favor the wheel-on-rail system.

The average distances between station in the Northeast Corridor, where the Acela Express runs, (average station spacing: 65 kilometers (40 miles)[31]) and the proposed average distance for the new high-speed rail system in California (63 kilometers (39 miles)[32]) are similar to those distances that Breimeier (2002, p. 29) assumes to be the maximum spacing for densely-populated Germany (75 kilometers (47 miles)). For almost all other regions in the United States, which are less densely populated, distances between stations for high-speed systems with travel speeds of 300 km/h (186 mph) and above can be assumed to be larger. The following benefit values (cf. Table 58) for this category have been determined.

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[31] The Acela Express that runs the Northeast Corridor stops a minimum of ten times in the 650 kilometers between Boston and Washington which means an average distance between stops of at most 65 kilometers.

[32] For the proposed 695-kilometer run between San Francisco and Los Angeles eleven intermediate stops are planned which equals an average distance between stations of 63 kilometers.

Table 58: Benefit Rating for Varying Distances between Stations

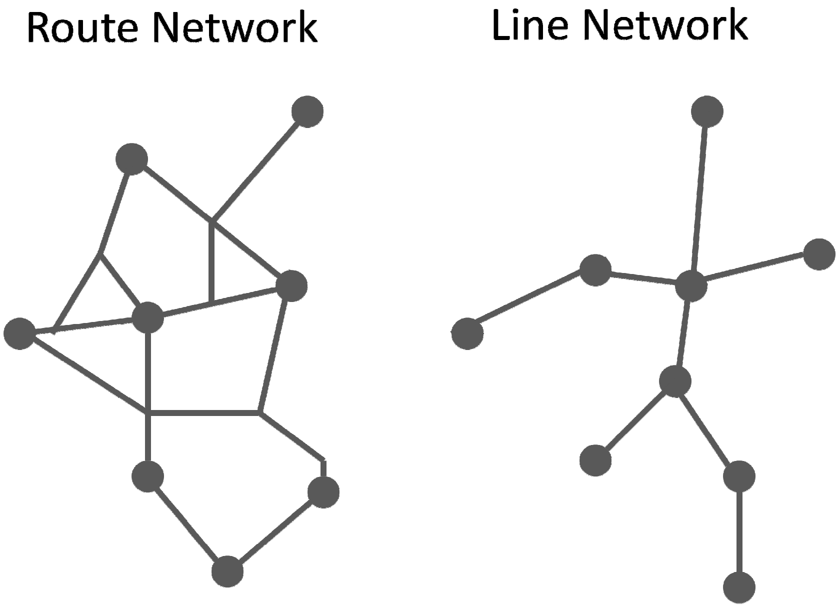
	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	4	4	4

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.5.7. Ability to Create a Connected High-Speed Ground Transportation Network

In general, one can distinguish between two different types of railroad networks: 1) 'Route networks' have a high number of connections between different railroad tracks (located both at or near station and at many locations along the different railroad tracks), and 2) 'Line networks' consisting of different railroad lines that run more linear and are mostly only connected at stations where they intersect each other. Figure 16 compares both types of railroad networks.

Figure 16: Different Types of Railroad Networks



The German network for high-speed trains (i.e. dedicated high-speed rail lines plus conventional rail lines, which are also used by high-speed trains) resembles a route network. High-speed trains can switch back and forth from dedicated high-speed lines to conventional railroad lines at several locations. Individual railroad tracks are used for several different travel routes, just as different train services use a variety of different tracks on an individual journey. The main reason for Germany's train network to resemble a route network is that a high number of conventional tracks are incorporated into the system. According to Vuchic and Casello (2002, p. 37), Germany has been the leader in upgrading existing rail lines. Dedicated high-speed rail tracks were added to the conventional lines where the related travel time savings were the greatest. By this procedure a highly interconnected network of high-speed rail and conventional rail lines emerged.

One important benefit of route networks like in Germany is that construction costs can be reduced by the incorporation of a large amount of already existing railroad tracks. Furthermore, through the high interconnectedness of the route network, a high number of different origin-destination pairs can be directly served (i.e. without intermediate transfers; cf. section 3.4.5 "Number of Transfers"). New links between different already existing tracks can be built in order to establish further traffic connections in case a respective demand is identified. The disadvantage of a route network is its significantly lower average travel speed due to the reduced speeds on the conventional railroad tracks. As such, these networks can contradict the goal to homogenize the rail networks in order to create high average speeds throughout the whole network (Guirao, 2005, p. 109).

The French, Spanish and Chinese high-speed rail networks resemble line networks. Each track of these networks is specifically designed for particular service. Different lines meet at comparatively few stations, which have, however, been strategically chosen to enable fast and convenient transfers from one line to another. Schach, Jehle, and Naumann (2006, p. 202) argue that, for high-speed traffic, a line network is generally preferable as the required number of transfer is generally limited. Travel demands can be predicted very accurately through travel demand analyses. Therefore, line networks can be specifically designed to meet this travel demand. As such, a particularly high flexibility to be able to run trains on several different routes may not be necessary. Instead, connections at stations that serve different routes are optimized to create the best possible connection between all stations of the network.

As described in section 3.3.6 “Ability to Use Existing Railway Tracks”, maglev trains cannot use existing railroad tracks. Accordingly, a route network that includes a high amount of existing conventional railroad tracks is not viable for the maglev system. The only feasible network type for a high-speed maglev system is a line network. Furthermore, it has been argued that “maglev’s switches are much more complex than rail switches. Therefore maglev is less capable of serving different branches or interconnected networks.” (Vuchic & Casello, 2002, p. 43) While this technical property does not limit the creation of line networks, which do not need many switches, it underscores the unsuitability of the maglev system for route networks.

For the wheel-on-rail high-speed system, both types of networks are equally feasible. Even though there is a considerable number of limitations to the use of existing railroad tracks (e.g. limited speeds, potential incompatibility of electrification with double-stack container transportation etc.; cf. section 3.3.6 “Ability to Use Existing Railway Tracks”), there is no general physical incompatibility to use conventional railroad tracks like there is for the maglev system.

In sum, both high-speed systems are equally suitable for a line network, which can with respect to most existing high-speed rail networks, be deemed to be the more common network type. These networks offer good interconnectedness based on optimized transfer points. In case an even higher interconnectedness of the high-speed network is desired, a route network is the preferred network type. As this type of network is only viable for the wheel-on-rail high-speed system, this system is assigned a higher benefit value in this category (cf. Table 59). Among the two cases for the high-speed maglev system, the case with maximum speeds of 450 km/h (280 mph) is assigned a higher benefit value because its higher travel speed can outweigh a lower interconnectedness.

Table 59: Benefit Rating for Ability to Create a Connected HSGT Network

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	5	2	3

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.5.8. Integration with Existing Transportation Infrastructure

"Policy-makers often demand a better integration of the various modes of transportation (Grimme, 2006)." A good integration of all available modes of transportation is crucial to achieve a high efficiency of the whole transportation system and to be able to offer travelers access to the optimal mode of transportation for each individual trip. Accordingly, Joseph Szabo, head of the Federal Railroad Administration (FRA), is cited: "If we do this properly, people will be able to flow from auto to rail to air like they do in Europe or Asia, using the most efficient mode for each part of the journey (Rosenthal, 2010)."

While the previous sections (section 3.5.7 "Ability to Create a Connected High-Speed Ground Transportation Network") focused on the integration within the high-speed system, this section deals with the integration with other modes of transportation. As pointed out in the previous section, only the wheel-on-rail system is suitable for a 'route network', i.e. a network which has a high number of connections at different points of the network and allows for serving various origin-destination with a direct service (i.e. without transfers). Furthermore, the wheel-on-rail high-speed system has the technical capability to allow for conventional trains to be operated on the high-speed lines. Through a good coordination of schedules, a high system integration between high-speed rail and conventional rail (e.g. commuter rail) can be reached when both trains run on the same route and share a high number of transfer points. On the Madrid-Seville wheel-on-rail high-speed line, there are, for instance, five different train categories in use (Guirao, 2005, p. 111). As such, the wheel-on-rail high-speed system has to be judged to be superior in terms of integration with conventional passenger rail services.

To achieve a good integration with air traffic, it is necessary that high-speed rail networks have stops at major airports (Givoni & Banister, 2007). On the one hand, this offers travelers the opportunity to easily transfer from one transportation system to the other. On the other hand, HSGT stations at airport are the prerequisite for more advanced options of transportation systems integration. For example, HSGT systems can be used as a substitute for short-haul domestic flights that serve as feeder flights for long-haul international flights. Such a service can be combined with integrated ticketing and baggage claims so that a truly intermodal system integration can be achieved. Such a service, called 'AIRail'[33] has been in successful operation in Germany for a few years now. It offers a variety of advantages for both passengers and operators. The passengers can start their trip at a city-center train station at their point of departure, which potentially saves time. Within the booking system of the airline, the high-speed train service, which connects to the airport, is handled as a flight. The train station is handled as an airport. At the train station where AIRail is available, the traveler can claim their baggage and check in for the whole journey on one single ticket. The airline benefits

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[33] 'AIRail' is offered by Lufthansa and its cooperating airlines and Deutsche Bahn, Germany's national railroad company, between the city-center train stations of Stuttgart and Cologne (and newly Siegburg/Bonn) and the airport station at Frankfurt airport. http://www.bahn.de/i/view/GBR/en/prices/germany/airail.shtml Accessed August 8, 2010

from such a service as it can substitute potentially unprofitable short-haul feeder flights by just paying a fee to the high-speed train operating company.

The integration with other transportation systems like automobile, local transit or walking and biking has been addressed in section 3.4.7 “Accessibility of Stations”. As described in this section, the accessibility is largely dependent on the city’s efforts to create or improve local transit systems like metro, light rail, or bus networks. In California, those cities that will be connected to the California high-speed rail system are already undertaking respective efforts. In Los Angeles County, for instance, 68 percent of the voters approved a half-cent transportation sales tax that will generate up to $40 billion in revenue over the next 30 years aimed at expanding the region’s rail and busway network, including connections to the planned high-speed rail stations (The United States Conference of Mayors, 2010, p. 10). Also San Francisco is converting its Transbay Terminal into a new transit hub. It will host Bay Area Rapid Transit, Caltrain, Greyhound bus services, Amtrak and the new California high-speed rail system.[34]

In sum, both HSGT systems can be very well integrated with other modes of transportation. The integration with conventional passenger rail services is, however, better for the wheel-on-rail high-speed system, which leads to the benefit values shown in Table 60.

Table 60: Benefit Rating for Integration with Existing Transportation Infrastructure

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	5	4	4

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

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[34] http://enr.construction.com/infrastructure/transportation/2010/0505-BayAreaTrainTerminal.asp Accessed June 17, 2010

3.6.Political Aspects

3.6.1. Societal Acceptance

Skepticism towards passenger rail service in the United States has been prevalent almost half a century in the United States. This may be due in part to the partially weak reputation of Amtrak and the fact that in the United States the skepticism against publically-operated transportation systems is generally greater than in other countries. Increasing congestion, both with automobile and air travel, however, has increased the appreciation of travel alternatives during the last few years. Some indication of this change is shown in a recent survey in the Wall Street Magazine. Out of 446 survey participants, 69.1% (308 voters) answered “Yes” to the question “Will high-speed get anywhere in the U.S.”?[35]

Among the two HSGT systems compared in this thesis, maglev is arguably the more controversial system: While its image and attractiveness might be a bit higher than that of wheel-on-rail system (cf. section 3.4.9 “Image and Attractiveness”), there will surely also be people who are more skeptical about maglev than about wheel-on-rail high-speed rail due to its more sophisticated technology. As Raschbichler (2004, p. 14) points out, the whole development history of the maglev system was “subjected to intense pressure in terms of public expectations and the need for success. Each significant setback and each failure could have meant the end of the new transportation technology”, which underscores the higher skepticism towards the maglev system.

In 2002, Vuchic and Casello (2002, p. 47) mentioned the strong disputes among many professionals such as engineers and economists about the maglev system. According to them, there was at that time, however, much promotion for the system on a

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[35] http://online.wsj.com/community/groups/asias-question-day-783/topics/high-speed-rail-get-anywhere-us Accessed June 24, 2010

political basis. With respect to public acceptance, they noted how wheel-on-rail high-speed systems like the Japanese Shinkansen and the French TGV increased their level of acceptance over time. They argued that the important innovation that maglev brought was its improved capability for high-speed travel (as opposed to sophisticated technological properties). The public in some parts of the world has already demonstrated acceptance when wheel-on-rail high-speed systems were introduced, which was rather supported by large time savings rather than technical features (Vuchic & Casello, 2002, p. 44). However, in countries where the implementation of high-speed maglev has been proposed, people have in the past been rather reluctant to accept a high-speed maglev system. According to Thornton (2009, p. 1903), this is because the implementation of high-speed maglev systems has mainly been discussed in countries like Japan and Germany, where successfully-operating wheel-on-rail high-speed networks already exist.

In sum, the level of acceptance for wheel-on-rail high-speed system can be expected to be higher than that for high-speed maglev systems. Consequently, the following benefit values are assigned in Table 61.

Table 61: Benefit Rating for Societal Acceptance

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	4	2	2

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.6.2. Perceived Technological Maturity

The technological maturity for high-speed rail has been shown in many countries of the world. The first railway in the world that can be called high-speed rail reaching speeds of around 210 km/h (131 mph) was the Japanese Shinkansen wheel-on-rail bullet train that connects Tokyo and Osaka (Guirao, 2005, p. 109). Since then, the Shinkansen system has transported more than 3 billion passengers without any loss of life or severe injury (Liu & Deng, 2004, p. 23) (cf. section 3.7 "Safety Aspects"). Today more than 5000 kilometers (3108 miles) of high-speed railways (Guirao, 2005, p. 109) are operated in the world, most of them in Japan and Western Europe with a rapidly growing high-speed-rail network in the People's Republic of China.

The technical readiness of the Transrapid maglev has been proven as early as December of 1991 when the German Bundesbahn Zentralamt (BZA, Federal Railway Agency) presented a report, commissioned by Germany's national railway authority and seven recognized university institutes, in which the experts concluded that the Transrapid maglev system was "technically ready for application without any restrictions. This meant that there were neither system nor safety risks either in the overall system or in the subsystems; the prerequisites required for the public legal planning processes with concept planning and project approval processes were fulfilled; [and] the investment costs for the high-speed maglev system could be estimated with sufficient certainty (Raschbichler, 2004, p. 13)." Also, critics of the maglev system have agreed that "the maglev system can be considered to be technically and operationally feasible (Vuchic & Casello, 2002, p. 41)." Even though an advanced project for a maglev line between Berlin and Hamburg was cancelled (cf. section 3.6.4. "Political Feasibility"), "the maglev system industry was able to acquire its first comprehensive experience in the overall design of a maglev route with a length of 300 kilometers and the comprehensive operations and maintenance concepts (Raschbichler, 2004, p. 13)."

In 2004, Liu and Deng wrote that "the mature nature of high-speed rail operations in Japan, France, and Germany certainly has provided the wheel-on-rail system with rich experiences in construction, operation, and management, when compared the only test track data in Germany and a brief maiden journey in Shanghai started less than a year ago." Up to now (2010), however, the Shanghai maglev system, which opened for revenue service in January 2004 (Siemens, 2006c), has been in operated successfully for more than six years. While experience with wheel-on-rail high-speed rail is obviously still significantly greater than experience with maglev, there is a reasonable amount of successful operation experience with the maglev system. Before the opening of the Shanghai system, for example, there used to be certain operational situations like the passing of two trains with a relative speed of 900 km/h (559 miles), which could not be simulated on the test track in Germany for this facility having no section with two parallel tracks. Following the opening of the Shanghai maglev system, however, this and other critical situations could be tested.

Even though the maglev system has been in commercial operations for some years now, the overall technological maturity of the wheel-on-rail system is still significantly higher. In this section, more attention is paid to the attribute of “perceived” technological maturity which further increases wheel-on-rail rails superiority in this category and thus leads to the following benefit rating in Table 62.

Table 62: Benefit Rating for Technological Maturity

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	4	2	2

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.6.3. Potential for Further Development

Discussions about technological maturity and the potential for further development often lead to the impression that both might conflict with each other. In fact, a system that shows a high level of technological maturity can still have a huge development potential. For example, the automobile has already been perceived as a perfectly mature means of transportation in the fifties. Still, major improvements to this technology have been added every year since the fifties and there is still no foreseeable end in technological enhancements. This section evaluates the potential of development independently from other physical parameters.

Breimeier (2002, pp. 24-25) argues that there is no considerable potential for further development in the maglev system. Instead he focuses on the chances of the wheel-on-rail high-speed system for further development, which he sees in improvements of wheelsets, weight reduction, automatic operation, and other fields. He concludes that the wheel-on-rail system has a considerable potential for further development.

Other authors see the higher potential for further development in the maglev technology. They state that its innovative potential lies especially in its electronic subassemblies of the support and guidance system. They expect that microelectronic developments will help to further reduce the weight and volume of several components (Lobach & Köb, 2004, p. 63). It is also expected that the costs of the Transrapid maglev system can be decreased by means of further modularization and standardization (Blank, Engel, Hellinger, Hoke, & Nothhaft, 2004, p. 78).

Schach, Jehle, and Naumann (2006, p. 330) agree about the high potential of development of the Transrapid technology. In contrast to Breimeier, they only see a limited potential for innovations and development for the wheel-on-rail technology. They say that mechanical wear, weak acceleration performance, and the lower average speeds of the wheel-on-rail system are due to technological, safety-related, and economic limits. These facts do not contradict Breimeier’s aforementioned reasoning as much as they seem to. It is true for both systems that the maximum travel speeds that were taken as a basis for this thesis (i.e. 300 km/h (186 mph) for the wheel-on-rail high-speed system and 450 km/h (280 mph) for the high-speed maglev system) cannot be increased in any significant way. For the wheel-on-rail system this is due to mechanical wear whereas maximum speed of the high-speed maglev system is limited due to the disproportionally increasing aerodynamic drag with increasing speeds. As also stated above, there are for both systems many fields for technical improvements that can reduce weight, energy consumption, and costs. The potential for cost reduction is certainly higher for the maglev system as economies of scale (cf. section 3.3.1 ”Investment Costs”) have not yet been reached.

In sum, both systems offer a reasonable potential for further development. The maglev system has advantages due to its potential for cost cutting. Major changes in basic characteristics like speeds, however, cannot be expected. Based on these considerations, the benefit values are shown in Table 63.

Table 63: Benefit Rating for Further Development

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	3	4	4

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.6.4. Political Feasibility

The ultimate decision whether a transportation project will be realized or not is a political one. Fact-based reasoning can be undermined by political programs and campaigns.

One of the major setbacks in the history of the high-speed maglev technology was the cancellation of the Berlin-Hamburg maglev project. The official reasons for the cancellation of the project were increased investment costs and decreased projected ridership. Critics have argued that travel demand was overestimated right from the beginning to create the foundations for the planning of a profitable system that the Berlin-Hamburg line, in their opinion, never was. Others have argued that projected travel demands were lower in additional studies until the critical ridership for a profitable operation could not be reached anymore (Schach, Jehle, & Naumann, 2006, p. 61). Either way, the discussion about the project until its cancellation had a high political involvement (Raschbichler, 2004, p. 13).

Because many characteristics of the 292-kilometers (181 miles) long Berlin-Hamburg line that would have connected Germany's two largest cities appear to be generally favorable for the Transrapid maglev, the cancellation of this project raised the question: "If maglev is not feasible for that line, is there any potential for it in Germany (Vuchic & Casello, 2002, p. 39)?" Sequentially, the decision to abandon the Berlin-Hamburg project had a significantly greater meaning than just the cancellation of an individual project. Agencies around the world that were considering the implementation of a maglev line became alerted that the system might have unknown other shortcomings. As such, the Shanghai maglev system, the first Transrapid system in commercial operation, is only a comparatively short line which tellingly carries the official name 'Shanghai Magnetic Levitation *Demonstration* Operation Line'. Two other German planning efforts for maglev projects in Munich and the Ruhr region were also cancelled. Despite the cancellation of the Berlin-Hamburg project, these projects did, however, not represent the transportation market in which the maglev system is best implemented as pronouncedly. Especially, the proposed 'Metrorapid' maglev project in the Ruhr region (in the state of North Rhine-Westphalia), where the Transrapid maglev would have served as a kind of metropolitan commuter service with very short average station spacings of approximately 11 kilometers (7 miles), represents a challenging market for the maglev system. As opposed to the Berlin-Hamburg project where it is more questionable which impact political involvement had, it is known that one important impact stopping the 'Metrorapid' project in the Ruhr region was a crisis in the coalition of the two parties that governed the state of North Rhine-Westphalia at that time, i.e. the

Social Democrats (SPD) who generally supported the maglev system and the Green who opposed it[36].

In the United States, a country whose settlement pattern with many distant large cities appears to be very well suited for maglevs in many regions. However, a chief obstacle towards the implementation of high-speed ground transportation systems in general used to be lack of support from the White House(Rosenthal, 2010). That, however, changed when President Obama took office in 2009 and promised to make high-speed rail a legacy of his administration. As there is now a good amount of political support for HSGT in general, the important question is how much this political feasibility differs between wheel-on-rail high-speed rail and high-speed maglev. Many authors like Raschbichler (2004, p. 15) argue that “the realization of an application route in Germany [i.e. the country where the Transrapid maglev system was developed and publically funded] is decisive for the further development.” The fact that such a system does not exist yet continues to impair the political feasibility of maglev system in other countries (Liu & Deng, 2004, p. 26). While promoters of wheel-on-rail high-speed rail projects have to struggle with the more usual obstacles of new, large, and costly projects, promoters of high-speed maglev systems get additionally weakened by the lack of application for the systems they promote. Accordingly, the benefit values shown in Table 64 have been determined for this category.

Table 64: Benefit Rating for Political Feasibility

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	4	2	2

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

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[36] http://www.stern.de/wirtschaft/news/verkehr-aus-fuer-den-metrorapid-in-nrw-509782.html Accessed August 11, 2010

3.6.5. External Economic Effects

For both HSGT systems, it is clear that their implementation will, apart from introducing more diverse travel options, also affect the economy as a whole in a positive way. A recent report by the United States Conference of Mayors that included case studies of Los Angeles, Chicago, Orlando, and Albany concluded that “in all four cities, the introduction of high-speed rail service will significantly increase jobs, wages, business sales, and value-added Gross Regional Product (GRP) (The United States Conference of Mayors, 2010, p. 5). More precisely, high-speed ground transportation service can increase business productivity through travel-efficiency gains. These gains result from time and cost savings for users of the HSGT as well as for users of automobile and air travel. Automobile and airplane riders mainly benefit through relieved congestion. Additional benefits arise for travelers without car who are now able to travel to destinations that they could not reach before. Furthermore, the introduction of HSGT service can help expand visitor markets and generate additional spending. According to the study (The United States Conference of Mayors, 2010, pp. 6-7), “projections show that by 2035, HSGT can annually add roughly $255 million in the Orlando area; $360 million in the Los Angeles area; $50 million in the Chicago area; and more than $100 million in the greater Albany area.” It has also been projected that approximately 4,000 new jobs in hotels, restaurants, and retail will be created in the downtown area of Los Angeles following the implementation of a HSGT station. For downtown Chicago between 12,000 and 18,000 new jobs have been projected (The United States Conference of Mayors, 2010, pp. 12, 16). The introduction of HSGT services can also broaden regional job markets as it facilitates bringing together specialized needs of companies with more specialized workers. The existence of HSGT services also supports the growth of technology clusters and, finally, fosters economic development in the direct vicinity of its stations.

The construction of the infrastructure for either HSGT system as well as the production of the vehicles and other equipment will also have positive impacts on the economy. For both high-speed ground transportation systems, it can be assumed that the project implementation will be conducted by both foreign and domestic companies. For both high-speed systems expertise from foreign countries is necessary as there are no American companies specialized at either high-speed maglev systems or wheel-on-rail high-speed systems. Still, large portions of planning and construction can be achieved by domestic companies. Production processes can also be expected to take place inside the United States. On the Shanghai Transrapid maglev project, for example, "the Chinese [i.e. the domestic] side was responsible for the route and construction planning and the German side, under the central coordination of Transrapid International […], was responsible for the system design (Fürst, 2004, p. 42)."

HSGT furthermore has positive external economic effects because external costs decrease when people who used automobiles before switch to HSGT. For instance, the external costs of cars in the European Union (EU) were estimated to be five times as high as those of rail per passenger per kilometer, which is mostly due to higher accident costs of the automobile (Smith, 2003, p. 245). The external economic benefits that arise from erasing higher external economic costs of other modes of transportation can be expected to be approximately equal between the HSGT systems. Similarly, positive external effects from construction and production can be expected to be similar. These economic benefits that are generated from improved travel opportunities and connectivity, however, are assumed to be greater for the maglev system when it is travelling with higher speeds (i.e. 450 km/h – 280 mph). Summing up all individual external economic effects leads to the benefits values shown in Table 65.

Table 65: Benefit Rating for External Economic Effects

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	4	4	5

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.6.6. Suitability to Serve as a Showcase Project

In a global world, cities and regions compete they try to attract companies, employees, and tourists, which all help a city or region develop and strive. While the transportation system is, on one hand, among the main factors determining the quality of the living and business conditions of a region, an innovative transportation system can also, apart from its technical and economic performance, draw people's attention to a region for having something extraordinarily innovative or unique.

While in many European and East-Asian countries wheel-on-rail high-speed systems are relatively common, they would in the U.S. certainly grab attention for the region that has the first or the fastest one. This attention could in the first years be a beneficial side effect of the system. Since maglev has not been implemented yet in the U.S., the level of attention for such a system would arguably be even greater than that for a wheel-on-rail high-speed rail system. Also the more sophisticated technology of the maglev system could grab additional attention for the region where it is implemented.

Thus, the benefit value for the high-speed maglev system in the category "suitability to serve as a showcase project" (cf. Table 66) is a bit higher than that of the wheel-on-rail high-speed system, especially when it is operated with higher travel speeds.

Table 66: Benefit Rating for Suitability to Serve as a Showcase Project

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	3	4	5

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.7. Safety Aspects

3.7.1. Risk of Derailment

Because the undercarriage of the maglev train wraps around its guideway, many authors state that it is (virtually) impossible for a maglev to derail (Schwindt, 2004, p. 36) (Liu & Deng, 2004, p. 23). The wheel-on-rail high-speed system has a higher risk of derailment. In 2008, for example, an ICE high-speed train derailed in a tunnel of the Hannover-Würzburg high-speed line after having collided with a herd of sheep. Out of 148 passengers, 21 were injured. Some have said that the main cause for the accident was the fact that the track was not separated from its environment. The benefit of fencing is, however, debatable since fences cannot completely prevent animals from entering the track. In addition, fences can trap animals in the track area after unexpectedly having entered it.

Breimeier (2002, p. 24) points out that derailment should not necessarily be judged as something entirely negative. There are possible situations in which the overall damage is lower when the train derails and thereby slows down alongside the track instead of having a potentially more severe collision by staying on the track. While such situations are technically possible, the more important question is how much the risk of derailment increases or decreases safety for passengers.

The deadliest high-speed rail accident in history occurred in 1998 near Eschede in Northern Germany. An ICE high-speed train derailed when one of its wheels, which had broken shortly before due to a fatigue crack, passed over a switch. The derailed train then collided with a roadway bridge and caused this bridge collapse on the following cars of the train; 111 passengers died and 88 were injured. This disaster shows the possible consequences of a derailment and that it is generally safer if trains cannot derail at all. In France, three incidents have occurred where TGV trains derailed at high speeds. All incidents were free of fatalities. For the Japanese Shinkansen system, one non-fatal derailment (October 2004 near Usara) due to an earthquake (cf. section 3.7.4 “Safety in Case of Natural Disasters”) has been reported.

Summing up, the risk of a maglev derailment is far lower than that of wheel-on-rail high-speed trains. Despite the risk of derailment for wheel-on-rail high-speed trains, there have only been few derailments for which only one had a fatality. Derailments can be largely prevented due to high safety standards which are applied to today’s high-speed rail systems. The Japanese Shinkansen high-speed system, for instance, has been operating for more than 45 years and has transported more than 3 billion passengers without any loss of life or severe injury (Liu & Deng, 2004, p. 23). Given that both systems are very unlikely to derail, the benefit values shown in Table 67 are assigned.

Table 67: Benefit Rating for Risk of Derailment

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	4	5	5

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.7.2. Risk of Collisions with other Trains

As opposed to derailment accidents, collisions between trains cause death in a high number of cases. For a Transrapid maglev train, it is technically impossible to collide with another maglev train since only one train can be in each drive control zone (cf. section 3.5.1 “Capacity”). The guideway motor is activated one section at a time and can operate in one direction only, which eliminates the risk of a collision with another maglev train (Siemens, 2006b, p. 13) (Schach, Jehle, & Naumann, 2006, p. 242) (Rausch, 2004, p. 22) (Liu & Deng, 2004, p. 23). Collisions between two maglev trains because of crossing maneuvers can also be excluded as two maglev tracks cannot cross. Instead a flyover must be constructed if it is desired that one track crosses the other. While such a construction increases the construction costs, this can be seen as a system-inherent security measure that prevents the collision of two maglev trains.

A collision of two wheel-on-rail trains is also extremely improbable due to advanced control systems that are designed specifically to prevent such incidents. These control systems provide that "vehicle movements only take place on secured routes. This means that the path to be taken by a vehicle is exclusively reserved for this vehicle. No other vehicle may be located on the track section reserved for this vehicle run or be able to move into it (Schünemann, 2004)." In contrast to the maglev high-speed system where tracks never cross on the same level, a collision between trains, however, is not physically impossible. Also, "it cannot systematically be excluded that two trains are on the same track heading towards one another (Schach, Jehle, & Naumann, 2006, p. 241)." Security systems, however, would automatically brake the trains if they were driving on one track facing each other. The only accident in the history of high-speed rail where a high-speed train collided with another rail vehicle occurred in April of 2006 in Thun, Switzerland, when an ICE train collided head-on with a set of locomotives. The driver of the set of locomotives had missed a signal, which made the emergency brake stop the locomotives automatically. Even though the emergency brake of the ICE train had decelerated the movement of the train, it still hit the locomotives with a speed of approximately 50 km/h (31 mph). Some passenger suffered minor injuries.[37] Apart from this event, no collision of any wheel-on-rail high-speed train with another rail vehicle could be identified.

Because a collision between two maglev trains is excluded and a collision between wheel-on-rail high-speed trains and other rail vehicles is very unlikely, the

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[37] http://www.focus.de/reisen/diverses/ice-unfall-in-thun_aid_108280.html Accessed July 29, 2010

following values for risk of collision with other trains shown in Table 68 have been determined.

Table 68: Benefit Rating for Risk of Collision with other Trains

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	4	5	5

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.7.3. Risk of Collisions with other Modes of Transportation and Environment

Collisions with other modes of transportation occur, in contrast to other major accidents, comparatively frequently. In particular, at-grade roadway crossings pose a risk for collisions between trains and other modes of transportation. That is why the design of new high-speed rail tracks does not include any at-grade crossings. As pointed out in section 3.3.6 “Ability to Use Existing Railway Tracks”, French TGV trains, for instance, partially run on tracks that were originally designed for conventional railroad operation, called ‘lignes classiques’ (classical lines). At-grade crossing do exist on these lines. At least four collisions of TGV trains with trucks and other road vehicles have been reported (September 1988 near Voiron, September 1997 near Dunkerque, January 2003 near Esquelbecq, and December 1997 near Tossiat). One of these collisions caused the death of two people on the train. The other accidents caused the death of one truck driver and injuries among people on the train. Following these accidents, an effort was made to remove all at-grade crossings on conventional rail lines (i.e. lignes classiques) that are used by TGV trains.

In case a derailment occurs, it is often fatal if the train collides with solid structures next to the track. Such a collision was the distinguishing factor that made one of the two ICE derailments mentioned in section 3.7.1 “Risk of Derailment” so much more severe than the other. The train, which had collided with the herd of sheep, slid along the wall of a tunnel for more than one kilometer before it stopped without colliding with anything except the wall on which it slid. The ICE train, which derailed when a broken wheel passed over a switch near Eschede, hit the structures of a bridge immediately after the derailment, which caused the bridge to collapse. The following cars of the train then collided with the collapsing bridge.

As discussed in section 3.7.1 “Risk of Derailment”, it is almost impossible for a maglev train to derail. Not being able to leave the guideway prevents maglevs from colliding with structures alongside the track. Due to the design of the guideway, at-grade crossings are precluded so there is no chance for a maglev train to collide with roadway traffic. The only thinkable case for a collision would be if objects were located on the maglev guideway. These situations are addressed in section 3.7.6 “Sensitivity towards Obstructions on Guideway”.

In sum, the maglev can technically not collide with other modes of transportation or with structures alongside the track. Wheel-on-rail high-speed trains (i.e. those with maximum travel speeds of 300 km/h, which are considered in this thesis) mostly travel on dedicated high-speed tracks that have no at-grade crossings. Accordingly, the risk of collision with other modes of transportation is also significantly lower than for conventional railway or so-called high*er*-speed rail, which uses upgraded conventional railroad tracks that usually have a high number of at-grade crossings. Consequently, the benefit values shown in Table 69 were assigned.

Table 69: Benefit Rating for Risk of Collision with other Modes of Transportation

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	4	5	5

1 = Minimum Benefit Value;   5 = Maximum Benefit Value

3.7.4. Safety in Case of Natural Disasters

Natural disasters that can affect high-speed ground transportation include earthquakes, floods, and landslides. Other natural disasters like tornados and hurricanes are predictable enough so that they do not pose a direct risk in terms of safety even though they may affect operations. In particular, earthquakes can represent a significant safety risk for the operation of wheel-on-rail high-speed trains as they usually occur unpredictably and directly affect the wheel-rail interaction of the wheel-on-rail high-speed system. Thus, a traveling train is subjected to a considerable risk of derailment in case of an earthquake. The only way to address this risk is to emergency-brake the train immediately when an earthquake is detected.

Interestingly, Japan, the country which was the pioneer in introducing high-speed rail as early as 1964, is also one of the countries with the highest frequency of earthquakes in the world. Accordingly, coping with the risk of earthquakes was one of the challenges in implementing high-speed rail in Japan. Today, most of the lines are equipped with an earthquake warning system. In case a larger earthquake is detected, the emergency brake is automatically applied. On some lines the application of this earthquake warning systems limits speeds as times until coming to a complete stop cannot be too high in order to ensure the effectiveness of an emergency braking maneuver. There is one incident in October 2004, when a Shinkansen train derailed in commercial operation due to an earthquake, which measured 6.8 on the Richter scale. Even though the emergency brake was applied, the train derailed near Urasa. Because the speed was already reduced at the time of derailment, the train came to standstill very quickly and nobody was severely injured. As pointed out before, there has been no fatality or severe injury among passengers of the Shinkansen system in more than 45 years of operation. This illustrates the fact that the wheel-on-rail high-speed system is capable of operating safely in an environment with a high earthquake frequency.

As discussed in section 3.7.1 “Risk of Derailment”, the maglev system is close to impossible to derail. This is also true in case of an earthquake. However, the system is still sensitive to ground motions as the gap between the guideway magnets and the undercarriage of the train is only 10 millimeters (0.4 inches). To ensure safety in case of an earthquake, a warning system that automatically slows down the train should be applied to the maglev system in regions with a high earthquake frequency. Not only might a maglev get damaged when its undercarriage contacts its guideway due to ground motions, but guideway beams be moved or dislocated in case of a very strong earthquake. Dislocated guideway beams pose a risk of a catastrophic accident that underscores the importance of an emergency brake in case of a strong earthquake. Due to its very strong braking power (cf. section 3.1.2 “Braking Performance”), the maglev system is very well suited for the application of an automatic emergency braking system since it could come to a stop very quickly.

Other natural disasters like landslides or flooding might either damage the track or cover it. One crucial question in determining the consequences of such events is whether damage gets detected before a train reaches the site. This is not dependent on the train system, but on surveillance procedures. An elevated guideway, which is more common for the maglev system, is less likely to be affected by a landslide than an at-grade track.

In sum, both high-speed systems should be emergency-braked in case of an earthquake. The risk that a severe accident happens due to an earthquake can be expected to be higher for the wheel-on-rail system due its higher risk of derailment and its weaker braking performance. In case of other natural disasters like landslides or flooding, the maglev system has slight advantages due to its higher percentage of elevated guideways. Because natural disasters do not occur very often, the benefit values of both systems do not differ too much. They are shown in Table 70.

Table 70: Benefit Rating for Safety in Case of Natural Disasters

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	4	5	5

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.7.5. Risk of Material Fatigue

Material fatigue can happen when material is subjected to repeated loading. If the loads are above a certain level, microscopic cracks can form, grow, and ultimately weaken the material. As explained in section 3.1.4 “Wear and Degradation”, the Transrapid high-speed maglev system travels on its guideway contact-free and is thus not subject to mechanical wear and tear. Still, loads are applied to its guideway and the vehicle while traveling. These loads could technically also cause material fatigue. Due to the contact-free support, however, no mechanical friction or vibrations are applied to the guideway and the undercarriage of the vehicle. So, two factors that have the highest significance in causing failure of certain parts do not exist on the maglev system.

To prevent accidents or malfunctions on the wheel-on-rail high speed system, those parts of the system that wear have to be changed regularly. Corresponding to high safety margins and strict maintenance procedures, there have only been a few incidents where failing parts have caused an accident. In October 2001, a TGV train derailed near Dax due to a broken rail. Also, two ICE accidents discussed above (cf. sections 3.7.1 “Risk of Derailment” were due to material failure. The low-speed derailment of an ICE train near Cologne central station in July 2008 was caused by a cracked axle. The Eschede train disaster of 1998, the deadliest accident in the history of high-speed rail with 101 fatalities, was caused by a broken wheel that caused the derailment of the train before it collided with a bridge.

In sum, the risk that an accident occurs on the wheel-on-rail system is, due to high safety standards, very low. However, there are a few cases where accidents were caused due to material fatigue. The high-speed maglev system has an even lower risk of accidents due to material fatigue as it is not subjected to certain mechanical effects (i.e. friction, vibration) that are most prominent in causing material fatigue. Table 71 shows the benefit ratings assigned for this category.

Table 71: Benefit Rating for Risk of Material Fatigue

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	4	5	5

1 = Minimum Benefit Value;   5 = Maximum Benefit Value

3.7.6. Sensitivity towards Obstructions on Guideway

For any high-speed ground transportation system, it is possible for obstructions to somehow make it onto the guideway. Obstructions may end up on a HSGT system guideway due to natural influences (e.g. landslides), due to mistakes by third parties (e.g. objects falling onto the guideway from overpasses or bridges), or even due to sabotage. Vehicles that might be located on the guideway and cause a collision have already been addressed in section 3.7.3 “Risk of Collisions with other Modes of Transportation and Environment”. It is agreed that “a collision with obstructions on the track like stones or other heavy, solid objects can cause the derailment of a wheel-on-rail-on rail high-speed train (Schach, Jehle, & Naumann, 2006, p. 241).” Similarly, a landslide may cause the derailment of the train. In general, the wheel-on-rail high-speed system is comparatively sensitive to obstructions on the guideway. To prevent objects from getting on the guideway, many countries consider it best practice to design crossings in a way that no other mode of transportation can travel on a higher crossing level than the rail systems. The benefits of this practice apply for both HSGT systems.

Due to the very small risk of a derailment for the maglev system, it is in general less sensitive to obstructions on the guideway. While the gap between the guideway magnets and the undercarriage of the train is only 10 millimeters (0.4 inches), the distance between the surface of the guideway and the underside of the vehicle is 150 millimeters (5.9 inches) (Transrapid International, 2006, p. 4) (Blank, Engel, Hellinger, Hoke, & Nothhaft, 2004, p. 65). This means that the Transrapid maglev can hover over small objects or a layer of snow, which may be located on top of the guideway. Also, the design of the Transrapid maglev takes into account the possibility of solid obstructions on its guideway. “The deformation elements and the support construction are designed to ensure operating safety […] [in the event of a] collision of the nose with a 50 kilogram (110 pound) stone lying in the middle of the guideway at 500 km/h (311 mph) or a collision of the nose with a tree trunk […] at 500 km/h (311 mph) (Lobach & Köb, 2004, p. 56).” While the train would obviously get damaged from such a collision, people on the train would not be expected to suffer any substantial injuries.

Still, the only fatal accident that ever involved the Transrapid maglev was due to an obstruction on the guideway. In September 2006, a maglev train collided with a heavy maintenance vehicle that was located on the guideway of the Emsland test facility (TVE) in Germany. The collision caused the death of 23 people. The lawsuit that followed two years later concluded that the tragedy was caused by a chain of human errors. Multiple staff members had committed multiple failures that led to the accident. Amongst other failures, they had failed to set an electronic braking system that would have prevented the train from operating while the maintenance vehicle was located on the track. Hence, two staff members were found guilty on 23 counts of manslaughter and 11 counts of causing negligent injury.[38] This accident harmed the safety reputation of the Transrapid high-speed maglev system even though it was proved that it only happened because operating staff disobeyed safety measures.

With respect to sabotage, the wheel-on-rail high-speed system is more sensitive. A solid object, which could theoretically be placed on the guideway by an individual, can cause the derailment of a wheel-on-rail high-speed train and thus, in the worst case, cause a deadly accident. By contrast, there is very little chance that an individual could cause a lethal accident of the maglev system. As derailment is close to impossible, an object of several tons would have to be placed on the guideway to cause a comparatively severe accident. Furthermore, the guideway of the maglev system, assumed to be constructed as an elevated guideway on the main part of a given route segment, can be expected to be less accessible than a track of a wheel-on-rail rail system. There is also very little chance to sabotage the substructure of the elevated guideway because it is a solid concrete structure.

Due to the in generally higher sensitivity towards obstruction of the guideway, the wheel-on-rail high-speed system is assigned a lower benefit value shown in Table 72.

Table 72: Benefit Rating for Sensitivity towards Obstructions on Guideway

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	3	5	5

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

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[38] http://www.welt.de/vermischtes/article2025517/Transrapid_Prozess_Geldstrafen_verhaengt.html Accessed July 14, 2010

3.7.7. Perceived Level of Safety by Users

The perceived level of safety describes how comfortable in terms of safety users feel riding a transportation system. Despite the well-known fact that traveling by car is statistically significantly more dangerous than traveling by airplane, a considerable amount of people suffer from a fear of flying. This fear of flying is not related to a factual higher safety risk, but to the subjective feelings it creates in its users. As such, fear of flying may be related to other fears like the fear of height, the fear of being in a closed space, the fear of not being in control, and others.[39]

The consideration of the fears related to the fear of flying gives an impression what kind of fears might be related to riding the Transrapid high-speed maglev system as opposed to riding a wheel-on-rail high-speed train. As pointed out in section 3.1.7 “Flexibility in Track Alignment”, one of the major benefits of the Transrapid maglev system is that it is well-suited for an elevated guideway. Even though not comparable to flying on an airplane, the feeling of being in a closed space will arguably be perceived more strongly on a maglev train than on a wheel-on-rail high-speed train. Similarly, the feeling of being out of control might be experienced more strongly due to the elevation of the maglev guideway. Passengers realize that they have to rely, in case of an emergency, the safety concept that will guide the train to the next station or an auxiliary stopping area (cf. section 3.7.8 “Evacuation of Trains”). While such a safety system increases safety from an objective point of view, it might be perceived as just the opposite by passengers who suffer from the aforementioned fears. They might feel more uncomfortable if they realize they could not break a window and climb out of the train.

While these fears will not be as strong as on an airplane, the system characteristics of the maglev systems appear to have a higher potential to cause these

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[39] http://www.airsafe.com/issues/fear.htm Accessed July 28, 2010

fears than the wheel-on-rail high-speed system. The two HSGT systems are assigned the benefit values shown in Table 73.

Table 73: Benefit Rating for Risk of Derailment

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	4	3	3

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.7.8. Evacuation of Trains

Trains can be evacuated for several reasons: Fire, long-lasting power outages that prevent the train from continuing its travel, or a collision with objects that damage the train. For such cases, the Transrapid maglev system is designed to be able to travel to the next station or an auxiliary stopping area.

In case the power supply fails while the vehicle is running, only the propulsion is lost. Because levitation and all on-board equipment are supplied from on-board batteries, the vehicle continues to levitate and move forward. The on-board eddy-current brakes are then applied such that the vehicle comes to a stop at either the next station or the next auxiliary stopping area (cf. section 3.5.2 "Reliability"). The auxiliary stopping areas are located along the route at a distance of typically 3 to 8 kilometers and are set up so that convenient access is provided for support services in case they are required (Rausch, 2004, p. 19) (Transrapid International, 2006, p. 12) (Schünemann, 2004, pp. 82-83). Thus, the Transrapid requires no access roads alongside its guideway (Siemens, 2006b).

Wheel-on-rail high-speed trains have to be expected to stop at any location on their route in case of one of the aforementioned emergency situations. Predefined auxiliary stopping areas are uncommon for the wheel-on-rail high-speed system. Because the track of wheel-on-rail high-speed systems is usually at-grade, passengers can theoretically just disembark the train. It might, however, be difficult for rescue teams to reach the train when it is stopped at a random location. Concerning this point of comparison, the maglev system, which only stops at predefined auxiliary stopping areas, has the advantage.

Theoretically, there is only one case thinkable that could cause a Transrapid maglev train to come to a stop apart from auxiliary stopping areas or stations. This case is a severe collision on the guideway. As pointed out in section 3.7.6 “Sensitivity towards Obstructions on Guideway”, the Transrapid maglev is designed to continue travelling even after a collision with heavy objects like tree trunks. The Transrapid maglev system not crossing any other transportation facilities at-grade, excludes collision with a vehicle of another mode. The only thinkable obstruction on the maglev guideway that is heavy enough to cause a severe collision that causes the maglev train to stop outside a station or auxiliary stopping area is a maintenance vehicle located on the guideway. Such a collision is, however, excluded by the electronic security system, which does not allow a maglev vehicle to travel a guideway when a maintenance vehicle is located on it. However, this collision still happened on the Emsland fest facility (TVE) in Germany in 2006 (cf. section 3.7.6 “Sensitivity towards Obstructions on Guideway”) after a series of errors by the operation crew. Among other human errors, the operators had disabled an electronic safety brake, which would have disallowed the operation of any maglev train in case a maintenance vehicle was located on the guideway. It was difficult to evacuate the train because it was stopped on an elevated guideway section apart from any station or auxiliary stopping area. Even though a stop at such a location is theoretically excluded, reality has shown that such stops might happen in a worst case scenario. In unexpected situations, the wheel-on-rail has advantages over maglev. Its track is more easily accessible because it is mostly designed at-grade. Furthermore, tracks often have access roads alongside the track, which are normally used for maintenance procedures or in case of minor operational malfunctions, which might require a wheel-on-rail high-speed system to be evacuated at a random location on the track.

In sum, the maglev system through its intelligent safety concept, which includes auxiliary stopping areas for any expected operational interruption, has advantages over the wheel-on-rail system. This erases the need for an accessible guideway at random locations along the track. Exactly this fact, however, disadvantages the maglev system in very rare, unexpected situations when better accessibility of the guideway would be beneficial. Because these situations represent severe incidents that involve collisions, they have to be considered more strongly. This leads to the benefit values shown in Table 74.

Table 74: Benefit Rating for Evacuation of Trains

	Wheel-on-Rail High-Speed Rail (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Benefit Rating	4	3	3

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

CHAPTER 4

QUANTITATIVE EVALUATION

The previous chapter identified the benefits associated with two high-speed ground transportation systems – wheel-on-rail high-speed rail and high-speed maglev – with respect to 58 characteristics in 7 categories. It is clear that not all 58 characteristics in this comparison are of an equal importance. To determine weighting factors for each the 58 characteristics and their 7 categories, a survey (cf. Appendix A.2 "Survey") was conducted with 46 organizations including state departments of transportation, regional and nationwide high-speed rail associations and agencies, engineering and consulting firms, and national agencies (cf. Appendix A.1 "Organizations included in the Survey"). The participants were asked to assign values of importance from "0" (unimportant) through "6" (extraordinarily important) to each of the 58 system characteristics as well as the 7 respective categories category.

This chapter combines the benefits values assigned to the 58 points of comparison in chapter 3 "Systems Comparison" with the weighting factors for each point of comparison that were drawn from the survey (cf. Appendix A.2 "Survey"). Applying a Multi-criteria Decision Making (MCDM) approach (Yoon & Hwang, 1995), utility values for each of the 7 categories (e.g. technical aspects, environmental impacts, etc.) were calculate for each HSGT system. As a reminder, because the properties of a large number of the 58 system characteristics compared in chapter 3 change with different speeds, the maglev train appeared twice in this comparison. For the first step of the comparison, the maglev train was considered to travel with the same maximum speed as the wheel-on-rail high-speed train, i.e. at 300 km/h (186 mph). For the second step of the comparison, both train systems were considered to travel with their own technically feasible maximum speed, i.e. the wheel-on-rail high-speed train traveled with a maximum speed of 300 km/h (186 mph) while the high-speed maglev train traveled with a maximum speed of 450 km/h (280 mph). This approach addressed the changes in several of the 58 points of comparison due to changes in speed and, at the same time, kept the comparison as simple as possible.

For the determination of the utility values of each HSGT system for each of the 7 categories, the benefit values for each of the 58 characteristics of chapter 3 had to be normalized. The normalized benefit values $b_{i,j}$ for each characteristic *i* for HSGT system *j* were calculated according to the following formula:

$$b_{i,j} = \frac{B_{i,j}}{B^{max}}$$

where: $B_{i,j}$ = benefit value for the *i-th* characteristic for the *j-th* HSGT system

B^{max} = maximum benefit value

To develop the weighting factors (i.e. the values of relative importance), the values of importance of each of the 58 characteristics that were drawn from the survey (cf. Appendix A.2 "Survey") were also normalized. The weighting factors w_{ij} (i.e. the relative importance) for characteristic *i* for HSGT system *j* were calculated according to the following formula:

$$w_i = \frac{I_i}{\sum_{i=1}^{n} I_i}$$

where: I_i = importance value for the *i-th* characteristic, drawn from the survey

$\sum_{i=1}^{n} I_i$ = sum of all importance values in the respective category

Based on the weighting factor w_i and the normalized benefit value $b_{i,j}$, the utility of HSGT system *j* in each category of characteristics was calculated according to the following formula:

$$U_j = \sum_{i=1}^{n} w_i * r_{i,j}$$

where: w_i = weighting factor of characteristic *i*

$r_{i,j}$ = normalized benefit value of characteristic *i* for HSGT system *j*

4.1. Technical Aspects

Table 75 summarizes the benefit values that were assigned for all system characteristic discussed in section 2 “Technical Aspects”. The normalized benefit values for all system characteristics of this category are also shown in Table 75. As an example, the normalized benefit value $b_{Acc,Wheel-on-Rail\ HSR}$ for the category “acceleration” for the system “wheel-on-rail high-speed rail” was calculated as follows:

$$b_{Acc,Wheel-on-Rail\ HSR} = \frac{B_{Acc,Wheel-on-Rail\ HSR}}{B^{max}} = \frac{2}{5} = 0.4$$

Table 75: Benefit Values and Normalized Benefits Values for Technical Aspects

	Wheel-on-Rail High-Speed System (300km/h)	**Wheel-on-Rail High-Speed System (300km/h) (normalized)**	High-Speed Maglev (300km/h)	**High-Speed Maglev (300km/h) (normalized)**	High-Speed Maglev (450km/h)	**High-Speed Maglev (450km/h) (normalized)**
Acceleration	2	**0.4**	5	**1.0**	4	**0.8**
Braking Performance	3	**0.6**	5	**1.0**	4	**0.8**
Travel Speed	3	**0.6**	3	**0.6**	5	**1.0**
Wear and Degradation	2	**0.4**	4	**0.8**	4	**0.8**
Train Weight	3	**0.6**	5	**1.0**	5	**1.0**
Compactness of Train	4	**0.8**	5	**1.0**	5	**1.0**
Flexibility in Track Alignment	3	**0.6**	5	**1.0**	3	**0.6**
Driving Resistance	4	**0.8**	5	**1.0**	3	**0.6**
Integration of Stations into Cities	3	**0.6**	4	**0.8**	4	**0.8**

The survey (cf. Appendix A.2) produced the importance values shown in Table 76 for all characteristics of the category “Technical Aspects”. It also shows the weighting factors that were calculated based on the importance values. As an example, the weighting factor w_{Acc} for the category “acceleration” was calculated as follows:

$$w_{Acc} = \frac{I_{Acc}}{\sum_{i=1}^{9} I_i} = \frac{4.00}{35.03} = 0.11$$

According to the respondents, travel speed and integration of stations into cities were the most important technical aspects. The least important aspects in this category were the weight and the compactness of trains. Driving resistance shows the highest variance in its importance.

Table 76: Survey Results and Normalized Weighting Value for Technical Aspects

	Unimportant (0)	Hardly Important (1)	Somewhat Important (2)	Important (3)	More Important (4)	Very Important (5)	Extraordinarily Important (6)	Total Responses	Average Importance	**Weighting Factor**	Standard Deviation
Acceleration	0	0	1	9	1	7	2	20	4.00	**0.11**	1.21
Braking Performance	0	0	2	9	1	6	2	20	3.85	**0.11**	1.27
Travel Speed	0	0	1	1	8	6	4	20	4.55	**0.13**	1.05
Wear and Degradation	0	0	3	3	8	3	3	20	4.00	**0.11**	1.26
Train Weight	0	1	3	9	4	2	1	20	3.30	**0.09**	1.17
Compactness of Train	0	2	1	11	2	3	0	19	3.16	**0.09**	1.12
Flexibility in Track Alignment	0	0	1	4	8	5	2	20	4.15	**0.12**	1.04
Driving Resistance	0	2	2	8	2	5	1	20	3.45	**0.10**	1.39
Integration of Stations into Cities	0	0	0	4	4	10	3	21	4.57	**0.13**	0.98

Based on the normalized benefit values from Table 75 and the weighting factors values from Table 76, the utility values for technical aspects were calculated as described above. As an example, the utility for technical aspects for the “wheel-on-rail high-speed rail” system was calculated as follows:

$$U_{Wheel-on-Rail\ HSR} = \sum_{i=1}^{9} w_i * r_{i,Wheel-on-Rail\ HSR}$$

$$= 0.11 * 0.4 + 0.11 * 0.6 + 0.13 * 0.6 + 0.11 * 0.4 + 0.09 * 0.6$$

$$+ 0.09 * 0.8 + 0.12 * 0.6 + 0.10 * 0.8 + 0.13 * 0.6$$

$$= 0.60$$

Table 77 shows the calculated utility values for this category.

Table 77: Utility Values for Technical Aspects

	Wheel-on-Rail High-Speed System (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Utility Values	0.60	0.90	0.82

4.2. Environmental Impacts

Table 78 summarizes the benefit values that were assigned for all system characteristics discussed in section 3.2 “Environmental Impacts”. It also gives the normalized benefit values for all system characteristics of this category.

Table 78: Benefit Values and Normalized Benefits Values for Environmental Impacts

	Wheel-on-Rail High-Speed System (300km/h)	**Wheel-on-Rail High-Speed System (300km/h) (normalized)**	High-Speed Maglev (300km/h)	**High-Speed Maglev (300km/h) (normalized)**	High-Speed Maglev (450km/h)	**High-Speed Maglev (450km/h) (normalized)**
Land Consumption	2	**0.4**	5	**1.0**	5	**1.0**
Energy Consumption	3	**0.6**	4	**0.8**	2	**0.4**
Noise Emissions	3	**0.6**	5	**1.0**	2	**0.4**
Interference with the Natural Environment	2	**0.4**	4	**0.8**	4	**0.8**
Suitability for Co-Alignment with other Transportation Infrastructure	2	**0.4**	4	**0.8**	2	**0.4**
Need for Construction of Structures (Bridges, Tunnels)	2	**0.4**	5	**1.0**	3	**0.6**
Aesthetic Impacts on Landscape and Cityscape	3	**0.6**	3	**0.6**	3	**0.6**
Barrier Effect (Physical Separation of Landscape and Cityscape)	2	**0.4**	4	**0.8**	4	**0.8**
Vibration	2	**0.4**	5	**1.0**	4	**0.8**
Material and Resource Consumption	3	**0.6**	3	**0.6**	3	**0.6**
Electromagnetic, Magnetic, and Electric Fields	4	**0.8**	2	**0.4**	2	**0.4**
Pollutant Emissions	5	**1.0**	5	**1.0**	5	**1.0**

The survey (cf. Appendix A.2) produced the importance values shown in Table 79 for all characteristics of the category “Environmental Impacts”. It also shows the weighting factors that were calculated based on the importance values. According to the respondents, energy consumption and pollutant emissions were the most important environmental impacts. The least important aspects in this category were aesthetics impacts and physical separation (barrier effects) of landscape and cityscape; vibration; and electromagnetic, magnetic, and electric fields. Pollutant emission shows the highest variance in its importance.

Table 79: Survey Results and Normalized Weighting Value for Environmental Impacts

	Unimportant (0)	Hardly Important (1)	Somewhat Important (2)	Important (3)	More Important (4)	Very Important (5)	Extraordinarily Important (6)	Total Responses	Average Importance	**Weighting Factor**	Standard Deviation
Land Consumption	0	0	6	6	6	4	0	22	3.36	0.08	1.09
Energy Consumption	0	0	2	4	4	9	3	22	4.32	0.11	1.21
Noise Emissions	0	0	1	9	6	6	0	22	3.77	0.09	0.92
Interference with the Natural Environment	0	0	1	8	3	6	4	22	4.18	0.10	1.26
Suitability for Co-Alignment with other Transportation Infrastructure	0	0	2	10	4	2	4	22	3.82	0.09	1.30
Need for Construction of Structures (Bridges, Tunnels)	0	0	1	4	10	5	2	22	4.14	0.10	0.99
Aesthetic Impacts on Landscape and Cityscape	0	2	3	11	3	3	0	22	3.09	0.08	1.11
Barrier Effect (Physical Separation of Landscape and Cityscape)	0	2	4	7	6	2	1	22	3.23	0.08	1.27
Vibration	0	2	2	10	4	3	0	21	3.19	0.08	1.12
Material and Resource Consumption	0	1	2	9	4	5	0	21	3.48	0.09	1.12
Electromagnetic, Magnetic, and Electric Fields	0	1	5	8	4	3	0	21	3.14	0.08	1.11
Pollutant Emissions	0	1	0	7	2	7	5	22	4.32	0.11	1.39

Based on the normalized benefit values from Table 78 and the weighting factors values from Table 79, the utility values for the category of environmental impacts shown in Table 80 were calculated.

Table 80: Utility Values for Environmental Impacts

	Wheel-on-Rail High-Speed System (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Utility Values	0.60	0.90	0.70

4.3. Economic Aspects

Table 81 summarizes the benefit values that were assigned for all system characteristics discussed in section 3.3 “ Economic Aspects”. It also gives the normalized benefit values for all system characteristics of this category.

Table 81: Benefit Values and Normalized Benefits Values for Economic Aspects

	Wheel-on-Rail High-Speed System (300km/h)	**Wheel-on-Rail High-Speed System (300km/h) (normalized)**	High-Speed Maglev (300km/h)	**High-Speed Maglev (300km/h) (normalized)**	High-Speed Maglev (450km/h)	**High-Speed Maglev (450km/h) (normalized)**
Investment Costs	4	**0.8**	2	**0.4**	2	**0.4**
Maintenance Costs	2	**0.4**	4	**0.8**	4	**0.8**
Operation Costs	3	**0.6**	4	**0.8**	4	**0.8**
Ridership Generation	4	**0.8**	4	**0.8**	5	**1.0**
Chances to Acquire Grants	4	**0.8**	3	**0.6**	3	**0.6**
Ability to Use Existing Railway Tracks	3	**0.6**	1	**0.2**	1	**0.2**

The survey (cf. Appendix A.2) produced the importance values shown in Table 82 for all characteristics of the category “Economic Aspects”. It also shows the weighting factors that were calculated based on the importance values. According to the respondents, ridership generation and operation cost were the most important economic aspects. The least important aspect in this category was the ability to use existing railway tracks. This characteristic, however, also shows the highest variance in its importance.

Table 82: Survey Results and Normalized Weighting Value for Economic Aspects

	Unimportant (0)	Hardly Important (1)	Somewhat Important (2)	Important (3)	More Important (4)	Very Important (5)	Extraordinarily Important (6)	Total Responses	Average Importance	**Weighting Factor**	Standard Deviation
Investment Costs	0	0	0	4	2	10	6	22	4.82	**0.15**	1.05
Maintenance Costs	0	0	0	1	5	10	6	22	4.95	**0.15**	0.84
Operation Costs	0	0	0	1	5	8	8	22	5.05	**0.16**	0.90
Ridership Generation	0	0	0	1	2	11	8	22	5.18	**0.16**	0.80
Chances to Acquire Grants	0	0	1	2	6	8	5	22	4.64	**0.14**	1.09
Ability to Use Existing Railway Tracks	0	2	1	2	3	10	4	22	4.36	**0.14**	1.50

Based on the normalized benefit values from Table 81 and the weighting factors values from Table 82, the utility values for economic aspects shown in Table 83 were calculated.

Table 83: Utility Values for Economic Aspects

	Wheel-on-Rail High-Speed System (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Utility Values	0.67	0.61	0.65

4.4. Aspects of User Friendliness

Table 84 summarizes the benefit values that were assigned for all system characteristics discussed in section 3.4 “ Aspects of User Friendliness”. It also gives the normalized benefit values for all system characteristics of this category.

Table 84: Benefit Values and Normalized Benefits Values for Aspects of User Friendliness

	Wheel-on-Rail High-Speed System (300km/h)	**Wheel-on-Rail High-Speed System (300km/h) (normalized)**	High-Speed Maglev (300km/h)	**High-Speed Maglev (300km/h) (normalized)**	High-Speed Maglev (450km/h)	**High-Speed Maglev (450km/h) (normalized)**
Travel Time	3	**0.6**	4	**0.8**	5	**1.0**
Arrival Frequency	5	**1.0**	5	**1.0**	5	**1.0**
Comfort	5	**1.0**	4	**0.8**	4	**0.8**
Travel Fare	5	**1.0**	5	**1.0**	5	**1.0**
Number of Transfers	4	**0.8**	2	**0.4**	3	**0.6**
Service	5	**1.0**	4	**0.8**	4	**0.8**
Accessibility of Stations	5	**1.0**	5	**1.0**	5	**1.0**
Baggage Transportation	5	**1.0**	5	**1.0**	5	**1.0**
Image and Attractiveness	4	**0.8**	5	**1.0**	5	**1.0**

The survey (cf. Appendix A.2) produced the importance values in Table 85 for all characteristics of the category “Aspects of User Friendliness”. It also shows the weighting factors that were calculated based on the importance values. According to the respondents, travel time, arrival frequency, and accessibility of stations were the most important aspects of user friendliness. The least important aspects in this category were baggage transportation and on-board services like catering. Number of transfers shows the highest variance in its importance.

Table 85: Survey Results and Normalized Weighting Value for Aspects of User Friendliness

	Unimportant (0)	Hardly Important (1)	Somewhat Important (2)	Important (3)	More Important (4)	Very Important (5)	Extraordinarily Important (6)	Total Responses	Average Importance	**Weighting Factor**	Standard Deviation
Travel Time	0	0	0	2	4	10	5	21	4.86	**0.14**	0.91
Arrival Frequency	0	0	0	1	8	6	6	21	4.81	**0.13**	0.93
Comfort	0	0	1	7	7	5	1	21	3.90	**0.11**	1.00
Travel Fare	0	0	1	2	12	5	1	21	4.14	**0.12**	0.85
Number of Transfers	0	0	2	9	1	6	3	21	3.95	**0.11**	1.32
Service	0	1	6	8	3	3	0	21	3.05	**0.09**	1.12
Accessibility of Stations	0	0	1	2	4	11	3	21	4.62	**0.13**	1.02
Baggage Transportation	0	3	5	6	6	1	0	21	2.86	**0.08**	1.15
Image and Attractiveness	0	0	4	5	7	5	0	21	3.62	**0.10**	1.07

Based on the normalized benefit values from Table 84 and the weighting factors values from Table 85, the utility values for aspects of user friendliness shown in Table 86 were calculated.

Table 86: Utility Values for Aspects of User Friendliness

	Wheel-on-Rail High-Speed System (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Utility Values	0.90	0.87	0.92

4.5. Operations

Table 87 summarizes the benefits values that were assigned for all system characteristics discussed in section 3.5 “ Operations”. It also gives the normalized benefit values for all system characteristics of this category.

Table 87: Benefit Values and Normalized Benefits Values for Operational Aspects

	Wheel-on-Rail High-Speed System (300km/h)	**Wheel-on-Rail High-Speed System (300km/h) (normalized)**	High-Speed Maglev (300km/h)	**High-Speed Maglev (300km/h) (normalized)**	High-Speed Maglev (450km/h)	**High-Speed Maglev (450km/h) (normalized)**
Capacity	5	**1.0**	4	**0.8**	4	**0.8**
Reliability	5	**1.0**	5	**1.0**	5	**1.0**
Dwell Time at Stations	4	**0.8**	3	**0.6**	3	**0.6**
Flexibility in Operation	3	**0.6**	1	**0.2**	1	**0.2**
Achievable Speeds in Urbanized Areas	3	**0.6**	5	**1.0**	5	**1.0**
Suitability for Varying Distances between Stations	4	**0.8**	4	**0.8**	4	**0.8**
Ability to Create a Connected High-Speed Rail Network	5	**1.0**	2	**0.4**	3	**0.6**
Integration in Existing Transportation Infrastructure	5	**1.0**	4	**0.8**	4	**0.8**

The survey (cf. Appendix A.2) produced the importance values given in Table 88 for all characteristics of the category “Operational Aspects”. It also shows the weighting factors that were calculated based on the importance values. According to the respondents, reliability and integration into existing transportation infrastructure were the most important operational aspects. The least important aspects in this category were dwell times at stations and suitability for varying distances between stations. Capacity shows the highest variance in its importance.

Table 88: Survey Results and Normalized Weighting Value for Operational Aspects

	Unimportant (0)	Hardly Important (1)	Somewhat Important (2)	Important (3)	More Important (4)	Very Important (5)	Extraordinarily Important (6)	Total Responses	Average Importance	**Weighting Factor**	Standard Deviation
Capacity	0	0	0	1	6	11	3	21	4.76	**0.13**	0.77
Reliability	0	0	0	2	3	10	6	21	4.95	**0.14**	0.92
Stopping Time at Stations	0	0	0	8	4	8	1	21	4.10	**0.11**	1.00
Flexibility in Operation	0	0	2	5	6	3	5	21	4.19	**0.12**	1.33
Achievable Speeds in Urbanized Areas	0	0	1	5	7	6	2	21	4.14	**0.12**	1.06
Suitability for Varying Distances between Stations	0	1	0	8	4	5	3	21	4.00	**0.11**	1.30
Ability to Create a Connected High-Speed Rail Network	0	0	2	3	2	5	9	21	4.76	**0.13**	1.41
Integration in Existing Transportation Infrastructure	0	0	0	3	4	6	8	21	4.90	**0.14**	1.09

Based on the normalized benefit values from Table 87 and the weighting factors values from Table 88, the utility values for operations shown in Table 89 were calculated.

Table 89: Utility Values for Operations

	Wheel-on-Rail High-Speed System (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Utility Values	0.86	0.70	0.73

4.6. Political Aspects

Table 90 summarizes the benefits values that were assigned for all system characteristics discussed in section 3.6 “Political Aspects”. It also gives the normalized benefit values for all system characteristics of this category.

Table 90: Benefit Values and Normalized Benefits Values for Political Aspects

	Wheel-on-Rail High-Speed System (300km/h)	**Wheel-on-Rail High-Speed System (300km/h) (normalized)**	High-Speed Maglev (300km/h)	**High-Speed Maglev (300km/h) (normalized)**	High-Speed Maglev (450km/h)	**High-Speed Maglev (450km/h) (normalized)**
Societal Acceptance	4	**0.8**	2	**0.4**	2	**0.4**
Perceived Technological Maturity	4	**0.8**	2	**0.4**	2	**0.4**
Potential for Further Development	3	**0.6**	4	**0.8**	4	**0.8**
Political Feasibility	4	**0.8**	2	**0.4**	2	**0.4**
External Economic Effects	4	**0.8**	4	**0.8**	5	**1.0**
Suitability to Serve as a Showcase Project	3	**0.6**	4	**0.8**	5	**1.0**

The survey (cf. Appendix A.2) produced the importance values given in Table 91 for all characteristics of the category “Operational Aspects”. It also shows the weighting factors that were calculated based on the importance values. According to the respondents, external economic effects, political feasibility, and potential for further development were the most important political aspects. The least important aspects in this category were suitability to serve as a showcase project and perceived technological maturity. Potential for further development shows the highest variance in its importance.

Table 91: Survey Results and Normalized Weighting Value for Political Aspects

	Unimportant (0)	Hardly Important (1)	Somewhat Important (2)	Important (3)	More Important (4)	Very Important (5)	Extraordinarily Important (6)	Total Responses	Average Importance	**Weighting Factor**	Standard Deviation
Societal Acceptance	0	0	1	3	6	10	1	21	4.33	**0.16**	0.97
Perceived Technological Maturity	0	0	2	6	4	8	1	21	4.00	**0.15**	1.14
Potential for Further Development	0	0	2	1	5	8	5	21	4.62	**0.18**	1.20
Political Feasibility	0	0	1	3	1	13	3	21	4.67	**0.18**	1.06
External Economic Effects (e.g. Creation of Jobs)	0	0	0	2	6	7	6	21	4.81	**0.18**	0.98
Suitability to Serve as a Showcase Project	0	0	3	6	4	7	1	21	3.86	**0.15**	1.20

Based on the normalized benefit values from Table 90 and the weighting factors from Table 91, the utility values for operational aspects shown in Table 92 were calculated.

Table 92: Utility Values for Operational Aspects

	Wheel-on-Rail High-Speed System (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Utility Values	0.74	0.60	0.67

4.7. Safety Aspects

Table 93 summarizes the benefit values that were assigned for all system characteristics discussed in section 3.7 “ Safety Aspects”. It also gives the normalized benefit values for all system characteristics of this category.

Table 93: Benefit Values and Normalized Benefits Values for Safety Aspects

	Wheel-on-Rail High-Speed System (300km/h)	**Wheel-on-Rail High-Speed System (300km/h) (normalized)**	High-Speed Maglev (300km/h)	**High-Speed Maglev (300km/h) (normalized)**	High-Speed Maglev (450km/h)	**High-Speed Maglev (450km/h) (normalized)**
Risk of Derailment	4	**0.8**	5	**1.0**	5	**1.0**
Risk of Collisions with other Trains	4	**0.8**	5	**1.0**	5	**1.0**
Risk of Collisions with other Modes of Transportation and Environment	4	**0.8**	5	**1.0**	5	**1.0**
Safety in Case of Natural Disasters (e.g. Earthquakes)	4	**0.8**	5	**1.0**	5	**1.0**
Risk of Material Fatigue	4	**0.8**	5	**1.0**	5	**1.0**
Sensitivity towards Obstructions on Guideway	3	**0.6**	5	**1.0**	5	**1.0**
Perceived Level of Safety by User	4	**0.8**	3	**0.6**	3	**0.6**
Easiness to Evacuate Train	4	**0.8**	3	**0.6**	3	**0.6**

The survey (cf. Appendix A.2) produced the importance values given in Table 94 for all characteristics of the category “Safety Aspects”. It also shows the weighting factors that were calculated based on the importance values. According to the respondents, risk of collision with other trains and risk of collision with other modes of transportation or the environment were the most important safety aspects. The least important aspect in this category was the risk of material fatigue. This category also shows the highest variance.

Table 94: Survey Results and Normalized Weighting Value for Safety Aspects

	Unimportant (0)	Hardly Important (1)	Somewhat Important (2)	Important (3)	More Important (4)	Very Important (5)	Extraordinarily Important (6)	Total Responses	Average Importance	**Weighting Factor**	Standard Deviation
Risk of Derailment	0	0	0	2	3	4	12	21	5.24	**0.12**	1.04
Risk of Collisions with other Trains	0	0	0	0	1	6	14	21	5.62	**0.13**	0.59
Risk of Collisions with other Modes of Transportation and Environment	0	0	0	0	1	7	13	21	5.57	**0.13**	0.60
Safety in Case of Natural Disasters (e.g. Earthquakes)	0	0	0	1	5	8	7	21	5.00	**0.12**	0.89
Risk of Material Fatigue	0	0	2	1	2	8	7	20	4.85	**0.12**	1.27
Sensitivity towards Obstructions on Guideway	0	0	1	1	2	6	10	20	5.15	**0.12**	1.14
Perceived Level of Safety by User	0	0	0	1	3	5	12	21	5.33	**0.13**	0.91
Easiness to Evacuate Train	0	0	0	1	4	6	9	20	5.15	**0.12**	0.93

Based on the normalized benefit values from Table 93 and the weighting factors from Table 94, the utility values for safety aspects shown in Table 95 were calculated.

Table 95: Utility Values for Safety Aspects

	Wheel-on-Rail High-Speed System (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Utility Values	0.78	0.90	0.90

4.8. Quantitative Evaluation for the HSGT Systems

Table 96 summarizes the utility values for both high-speed ground transportation systems that were calculated in the previous sections.

Table 96: Utility Values for both High-Speed Ground Transportation Systems

	Wheel-on-Rail High-Speed System (300km/h)	High-Speed Maglev (300km/h)	High-Speed Maglev (450km/h)
Technical Aspects	0.60	0.90	0.82
Environmental Aspects	0.60	0.90	0.70
Economical Aspects	0.67	0.61	0.65
Aspects of User Friendliness	0.90	0.87	0.92
Operational Aspects	0.86	0.70	0.73
Political Aspects	0.74	0.60	0.67
Safety Aspects	0.78	0.90	0.90

The survey (cf. Appendix A.2) produced the importance values given in Table 97 for all 7 categories comprising the 58 characteristics that were evaluated in chapter 3 and are the basis for the utility values shown in Table 96. Table 97 also shows the weighting factors that were calculated based on the importance values. According to the respondents, safety aspects were the most important category. The least important categories were technical and political aspects. Environmental impacts showed the highest variance in its importance value.

Table 97: Survey Results and Normalized Weighting Value for the seven Categories of Comparison

	Unimportant (0)	Hardly Important (1)	Somewhat Important (2)	Important (3)	More Important (4)	Very Important (5)	Extraordinarily Important (6)	Total Responses	Average Importance	**Weighting Factor**	Standard Deviation
Environmental Aspects	0	0	0	5	5	6	5	21	4.52	**0.14**	1.12
Economical Aspects	0	0	0	2	4	8	7	21	4.95	**0.15**	0.97
Aspects of User Friendliness	0	0	0	4	5	11	1	21	4.43	**0.14**	0.87
Technical Aspects	0	0	1	4	9	6	1	21	4.10	**0.13**	0.94
Operational Aspects	0	0	1	2	6	8	4	21	4.57	**0.14**	1.08
Political Aspects	0	0	1	4	4	11	0	20	4.25	**0.13**	0.97
Safety Aspects	0	0	0	1	1	6	13	21	5.48	**0.17**	0.81

Based on the utility values for the 7 categories from Table 96 and the weighting factors from Table 97, the overall utility values of the two high-speed ground transportation systems, including the two cases with different speeds for the maglev system, shown in Table 98 were calculated.

Table 98: Overall Utility Values for High-Speed Ground Transportation Systems

	Wheel-on-Rail High-Speed System (300 km/h)	High-Speed Maglev (300 km/h)	High-Speed Maglev (450 km/h)
Utility Values	0.73	0.79	0.77

CHAPTER 5

RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

5.1. Summary of Results

In the category of technical aspects (cf. section 4.1), the high-speed maglev system (utility values of 0.90 for the case with a maximum travel speeds of 300 km/h (186 mph) and 0.82 for the case with speeds of 450 km/h (280 mph)) is highly superior over the wheel-on-rail high-speed system (utility value of 0.60). The maglev system travelling at 300 km/h (186 mph) has the advantage over the wheel-on-rail high-speed system in 8 of 9 characteristics. Only for travel speed, both systems (wheel-on-rail HSR and maglev at 300 km/h (186 mph)) show equal benefit values. The superiority of the maglev system is most prevalent in terms of acceleration, having also considerable advantages in terms of braking performance, wear and degradation, and flexibility in alignment. If maximum travel speeds of the maglev system are increased to 450 km/h (280 mph), its utility value for technical aspects drops, which is due to decreasing benefit values in acceleration and braking performance, flexibility in track alignment, and driving resistance. In the direct comparison between the maglev system traveling at 450 km/h (280 mph) and the wheel-on-rail high-speed system, the maglev can maintain its advantages in 7 of 9 characteristics. While both systems are approximately equally flexible in track alignment, the wheel-on-rail high-speed system is superior over the faster-travelling maglev system in terms of driving resistance. According to the survey participants, travel speed and integration of station into cities are the most important characteristics in the category of technical aspects. By definition, the faster-travelling maglev system outperforms slower-travelling maglev and the wheel-on-rail high-speed system in terms of travel speed. Concerning integration of stations into cities differences between the three cases compared are less significant. The overall superiority of the maglev system travelling at 300 km/h (186 mph) in terms of technical aspects is due to its better performance concerning most of the remaining characteristics.

Concerning environmental impacts (cf. section 4.2), the maglev system travelling at maximum speeds of 300 km/h (186 mph) (utility value of 0.90) has the advantage over the faster-travelling maglev (i.e. at 450 km/h – 280 mph) (utility value of 0.70) as well as the wheel-on-rail high-speed system (0.60. It is in 8 of 12 environmental characteristics superior over the wheel-on-rail high-speed system, most prominently in terms of land consumption, noise emission, interference with the natural environment, suitability for co-alignment with other transportation infrastructure, need for construction of structures, barrier effect, and vibration. The two systems rank approximately equal in terms of aesthetic impacts, material and resource consumption, and pollutant emissions. Only with respect to electromagnetic, magnetic, and electric fields, the wheel-on-rail high-speed system has the advantage of the maglev system at 300 km/h (186 mph). By increasing the assumed maximum travel speed of the maglev system to 450 km/h (280 mph), the maglev's superiority over the wheel-on-rail system in energy consumption, noise emission, suitability for co-alignment, and need for construction of structures decreases significantly. In fact, it loses the advantages with respect to energy consumption and noise emission, two of the highest-ranked characteristics according to the survey, to the wheel-on-rail system. The maglev system traveling at maximum speeds of 450 km/h (280 mph) still performs considerably better than the wheel-on-rail system in land consumption, interference with the natural environment, barrier effects, and vibration. Having also a somewhat higher benefit than the wheel-on-rail system in terms of the need for construction of structures, it performs approximately equally well as the wheel-on-rail-system in terms of co-alignment, material and resource consumption, and pollutant emissions.

Both the wheel-on-rail high-speed system (utility value of 0.67) and the faster-travelling maglev system (i.e. 450 km/h – 280 mph) (utility value of 0.65) perform a bit better in the category of economic aspects (cf. section 4.3) than the maglev system travelling at maximum speeds of 300 km/h (186 mph) (utility value of 0.61). The wheel-on-rail system has considerable advantages over both speed cases of the maglev system in terms of investment costs and the ability to use existing railroad tracks. Furthermore, it has a slight advantage in terms of chances to acquire grants. With regard to maintenance, repair, and rehabilitation costs as well as operation costs, the maglev system performs better than the wheel-on-rail high-speed system, regardless of its assumed maximum travel speeds. Concerning ridership generation, the most important economic characteristic according to the survey participants, the maglev system travelling at 450 km/h (280 mph) has the advantage over the wheel-on-rail system and the slower-travelling maglev, which both perform approximately equal in this criterion.

With regard to user friendliness (cf. section 4.4) all three cases (i.e. the wheel-on-rail high-speed system and the two speed cases for the maglev system) show a very similar performance. The wheel-on-rail high-speed system (utility value of 0.90) ranges well between the two cases compared for the maglev system – travelling at maximum speeds of 450 km/h (280 mph) its utility value is 0.92; travelling at 300 km/h (186 mph) its utility value is 0.87. It performs somewhat better with regard to comfort, number of transfers, and service than both cases of the high-speed maglev system. These are, on the other hand, superior in travel time as well as image and attractiveness. Concerning arrival frequency, travel fare, accessibility of stations, and baggage transportation no significant differences between the three cases that were compared could be identified. The superiority in terms of travel times, according to the survey the most important characteristic in terms of user friendliness, is greater for the faster-travelling maglev. Also, the disadvantage of the maglev system with respect to the required number of transfers is less significant when the maglev is considered to travel at a maximum speed of 450 km/h (280 mph).

With respect to operations (cf. section 4.5), the wheel-on-rail high-speed system (utility value of 0.86) has considerable advantages over the high-speed maglev system, for both cases of maximum travel speed. The high-speed maglev system performs approximately equal for both maximum travel speeds (utility value of 0.70 for 300 km/h (186 mph) and 0.73 for 450 km/h (280 mph)) as both cases show equal benefit values for all system characteristics in the category of 'operations' except 'ability to create a connected high-speed network', where the maglev performs a bit better when faster maximum speeds (i.e. 450 km/h – 300 mph) are assumed. Showing similar benefits in terms of reliability and suitability for varying distances between stations, the high-speed maglev system has the advantage over the wheel-on-rail high-speed system in terms of achievable speeds in urbanized areas. With respect to capacity, dwell times at stations, and integration into existing transportation infrastructure the wheel-on-rail high-speed system is slightly superior over the high-speed maglev system for both speed cases. The wheel-on-rail system's superiority is more prevalent in terms of flexibility in operations and the ability to create a connected high-speed network, which is the most important characteristic in operations according to the survey results.

Concerning political aspects (cf. section 4.6) the wheel-on-rail high-speed system has the highest utility value (0.74). The maglev system travelling at 450 km/h (280 mph) (utility values of 0.67) ranged well between the wheel-on-rail high-speed system and the maglev system travelling at 300 km/h (186 mph) (utility value of 0.60). According to the survey, the three most important political aspects are potential for further development, political feasibility, and external economic effects. In terms of external economic effects, the faster maglev system (i.e. travelling at maximum speeds of 450 km/h (280 mph)) is associated with slightly higher benefits than the two other systems. The potential for further development is for both cases of the maglev system slightly higher than that of the wheel-on-rail high-speed system. The political feasibility, as well as the societal acceptance and the perceived level of maturity, however, is considerably better for the wheel-on-rail system, which is the reason why this system performs better in the summarized evaluation of political aspects. The suitability to serve as a showcase project, on the other hand, is higher for the two speed cases of the maglev project, the faster-travelling case having the advantage over the case where maximum travel speeds of 300 km/h (186 mph) are assumed.

In the category ‘safety’ (cf. section 4.7), the high-speed maglev system shows equal benefits values for both speeds considered in every category and, sequentially, also the same utility value (0.90) for the whole category. This leads to the conclusion that the safety of the high-speed maglev system does not change significantly with increasing travel speeds. The maglev system has the advantage over the wheel-on-rail high-speed system (utility value of 0.78) on every criterion except ‘perceived level of safety by users’ and ‘evacuation of trains’. Like in all remaining safety characteristics, the high-speed maglev system is superior over the wheel-on-rail high-speed system in terms of ‘risk of collisions with other trains’ and ‘risk of collision with other modes of transportation’, the criteria that were assigned the highest importance values among all safety aspects by the survey participants.

Summarizing the utility values that have been calculated for all seven comparison categories (cf. section 4.8 “Quantitative Evaluation for the HSGT Systems”) and weighting them according to the results of the survey, the overall utility value for the wheel-on-rail high-speed system is calculated as 0.73. By the same procedure, the overall utility value of the high-speed maglev system with an assumed maximum travel speed of 300 km/h (186 mph) is calculated as 0.79. The maglev system travelling at 450 km/h (280 mph) shows an overall utility value of 0.77.

5.2. Conclusions

Following the systems comparison in this thesis and the weighting of the various comparison characteristics according to the survey that was conducted with members of transportation departments and other transportation professionals, the high-speed maglev system is slightly superior over the wheel-on-rail high-speed system. For both cases of different assumed maximum travel speeds included in this thesis (300 km/h (186 mph) and 450 km/h (280 mph)), the high-speed maglev system shows slightly higher overall utility values than the wheel-on-rail high-speed system. The overall utility value of the maglev system travelling at a maximum speed of 300 km/h (186 mph) is 0.79, which is very close to the overall utility value of 0.77 that has been calculated for the maglev system travelling at maximum speeds of 450 km/h (280 mph). The overall utility value for the wheel-on-rail high-speed system is 0.77. This leads to the conclusion that the gain in benefit that is associated with implementing the high-speed maglev system as opposed to the wheel-on-rail high-speed system is almost independent of the maximum travel speeds applied to the maglev system.

The maglev system travelling at 300 km/h (186 mph) has the advantage over the wheel-on-rail high-speed system with regard to technical, environmental, and safety aspects. In terms of user friendliness both systems perform approximately equally well. Regarding economic, operational, and political aspects, on the other hand, the wheel-on-rail system is superior over the maglev system travelling at 300 km/h (186 mph). The fact that both systems are superior over the other in three categories each illustrates the limited magnitude of the overall advantage of the high-speed maglev system travelling at 300 km/h (186 mph) over the wheel-on-rail system. The slight superiority of the maglev system over the wheel-on-rail-system derives from the fact that the categories, where it perform better (e.g. safety aspects), were weighted more strongly according to the survey results.

The maglev system travelling at 450 km/h (280 mph) is superior over the wheel-on-rail system with respect to technical, environmental, and safety aspects. The magnitude of the maglev system’s superiority in terms of environmental aspects is, however, only one third as high as the magnitude of the slower maglev system’s environmental superiority over the wheel-on-rail high speed system. Similarly, the advantage in terms of technical aspects is smaller for the maglev system travelling at 450 km/h (280 mph). In terms of safety, however, the advantage of the faster-travelling maglev system over the wheel-on-rail high-speed has the same magnitude as the advantage of the maglev system travelling at 300 km/h (186 mph) has. Regarding economic aspects and user friendliness, the maglev travelling at 450 km/h (280 mph) and the wheel-on-rail high-speed system perform almost equally well. Concerning operational and political aspects, the wheel-on-rail system is better than the maglev system travelling at 450 km/h (280 mph), even though its advantage is not as great as its advantage over the maglev system travelling at 300 km/h (186 mph). In 5 of 7 categories, the utility values of the maglev system travelling at maximum speeds of 450 km/h (280 mph) range between the values of the wheel-on-rail system and the slower-travelling maglev system, which leads to the conclusion that the faster-travelling maglev system balances advantages the best, even though it is not the system with the highest absolute utility value in this evaluation.

Several system characteristics change if a maximum speed of 450 km/h (280 mph) is applied to the maglev system instead of a speed of 300 km/h (186 mph). The advantages that result from the speed increase (e.g. shorter travel times, higher ridership generation, better integration into existing transportation infrastructure, more positive external economic effects etc.) are almost exactly balanced out by disadvantages that are also associated with the speed increase (e.g. higher energy consumption, higher noise emissions, decreased flexibility in alignment etc.). On the one hand, this leads to the conclusion that the high-speed maglev system is for neither speed case – its own technical maximum speed of 450 km/h or maximum speed of 300 km/h (186 mph) that equals the technical maximum speed of the wheel-on-rail high-speed system – categorically better. Both cases of maximum travel speeds are associated with individual advantages and disadvantages that can only be optimized at the project level of a particular planning effort. On the other hand, the high-speed maglev system is for both speeds slightly superior over the wheel-on-rail high-speed system. This means that in planning efforts where the technical maximum speeds of the high-speed maglev system of 450 km/h (280 mph) is not feasible (e.g. due to noise protection requirements), the maglev system has, in general, still the advantage over the wheel-on-rail high-speed system.

It has also been shown that the utility values for both speed cases of the high-speed maglev system (i.e. with maximum travel speeds of both 450 km/h (280 mph) and 300 km/h (186 mph)) are not significantly higher than the utility value of the wheel-on-rail high-speed system. This leads to the conclusion that the number of advantages and disadvantages that both high-speed ground transportation systems have balance out each other to a large extent. Therefore, the best-suited technology for a given project can only be determined at the project level. Due to the similar overall utility of both systems, planning efforts and engineering studies that deal with ‘true’ high-speed transportation systems (i.e. high-speed ground transportation systems whose maximum seeds are close to 300 km/h (186 mph) or higher) should always evaluate both systems at least in the first planning stages. It would be a mistake to overrate a certain advantage of either system (e.g. the higher achievable travel speeds of the maglev system or the ability to use existing railroad tracks of the wheel-on-rail high-speed system) in an earlier stage of a planning effort and, thus, categorically exclude one system too early. Both HSGT systems should be examined to such an extent that it can with a good level of confidence be judged which system has the advantage over the other for the given project.

5.3. Recommendations

To reach a fully integrated transportation system, it is essential that travelers have the freedom to choose among a number of alternative modes for a given trip and that they can select the mode that is best-suited for each trip segment. Also, it is important that travelers have the opportunity to switch from one mode to another easily, which is the most characteristic part of the definition of an ‘integrated’ transportation system. High-speed ground transportation systems have in many other countries proved that they offer great advantages for travelers concerning economic, ecological, safety-related, and comfort-related aspects. Due to the advantages that high-speed ground transportation systems offer, any developed country should examine the benefits of the implementation of these systems. Accordingly, respective efforts to let the American traveler benefit from high-speed ground transportation system have been increased recently by dedicating $8 million in ARRA funds to high-speed rail. Even though promoted with the typical benefits of high-speed rail, the major portion of these funds went to conventional rail projects instead of (true) high-speed rail.

While conventional rail is another very important component of an integrated passenger transportation system, this thesis focused exclusively on high-speed ground transportation systems, i.e. those ground transportation systems that can reach maximum travel speeds of 300 km/h (186 mph) and more in commercial operation. As opposed to lower-speed passenger rail services, high-speed ground transportation systems are competitive with the automobile and the airplane in the long-haul market, which is one of the very characteristics of these systems.

Therefore, it is important that the term ‘high-speed’ rail be used exclusively for rail systems that fulfill this requirement. In order to present the benefits and capabilities of (true) high-speed rail to the public, it is essential that corresponding projects are successfully brought into commercial operation during the next years. The proposed high-speed rail projects for California, for example (next to the Florida project the only high-speed rail project funded with ARRA grants) has a very good chance to demonstrate the advantages of high-speed ground transportation system and thus set a solid foundation for the implementation of further high-speed ground transportation projects in the country.

This thesis has shown that both high-speed ground transportation system – the wheel-on-rail high-speed system and high-speed maglev – should be considered for any intercity passenger transportation project. Even though the maglev system is generally slightly superior over the wheel-on-rail high-speed system, both systems are on a similar level in terms of their utility values calculated in this thesis. For any given high-speed ground transportation planning effort, both HSGT systems should be considered in engineering studies until the best-suited HSGT system can be determined on the project level for a given planning effort.

This thesis can help planners and engineers to conduct preliminary general assessments concerning the suitability of either system. To develop tools to assess different HSGT system for a given high-speed transportation project, engineers and planners can start with the evaluation and comparison procedure applied in this thesis. To tailor the evaluation procedure in this thesis to their specific project, it would be recommendable to conduct surveys with potential customers, potential operators, potential investors and other stakeholders and have them weight the 58 characteristics from their personal perspective and with respect to the specific project. The results from different stakeholder perspectives as well as results for different planning efforts might differ considerably. They can then be incorporated into a project-specific comparison using the same methodology as used for the more general systems evaluation presented in this thesis. Also, engineers and planners might consider selecting subsets of characteristics that are particularly prevailing for a specific project. Such a project-specific evaluation based on this thesis can give directions for subsequent engineering studies.

In order to utilize the benefits of high-speed ground transportation systems as completely as possible, other national goals, apart from directly transportation-related goals, should be considered in the selection of HSGT system to the full extent. For example, diesel-powered trains which can reach speeds of up to 240 km/h (149 mph) and thus come close to the speed ranged of high-speed rail, have also been discussed for several corridors in the United States. Similar to electrically-propelled high-speed ground transportation systems, diesel-powered trains also have a potential to address many problems like increasing levels of traffic congestion. While they are with respect to environmental friendliness (e.g. greenhouse gas emissions) superior over the automobile and the airplane, diesel-powered trains do not offer the huge environmental benefits that electrically-driven high-speed trains do. The HSGT systems considered in this thesis offer the ability to use renewable sources of energy by a 100-percent share and thus take a major step towards limiting greenhouse gas emissions and becoming more independent of foreign oil imports.

Furthermore, operators of established modes (e.g. airlines) should not only see high-speed rail as a competitor. Instead, they should contribute to the promotion of a more integrated multimodal passenger transportation system by cooperation with high-speed rail operators. By giving travelers a wider choice of available modes for a planned trip, operators of certain services can also benefit by making their operations more efficient in that they can, for example, substitute unprofitable short-haul feeder flights by high-speed rail airport services that are arguably better-suited for this market segment.

The transportation system of United States can benefit largely from adding high-speed ground transportation as well-suited mode for intercity passenger transportation. To maximize this benefit, it is recommended that studies in this market segment consider all HSGT options available – the wheel-on-rail high-speed system and the high-speed maglev system.

APPENDIX

A.1. Organizations included in the Survey

Altogether 46 organizations were asked to respond to the survey. In total, 24 responses were received. Two responses which arrived late after the deadline were not considered. So, the quantitative evaluation in chapter 4 was based on 22 responses. Below is a list of all organizations that were asked to participate. Since anonymity was guaranteed, it is not known which 22 of these 46 organizations were among the respondents. The state departments of transportation that were included in the survey were selected based on a set of publications about regions where the implementation of high-speed ground transportation systems seems feasible as well as on the regions that received PRIIA and ARRA founds.

State Departments of Transportation
Alabama Department of Transportation
Arizona Department of Transportation
California Department of Transportation
Connecticut Department of Transportation
Delaware Department of Transportation
Florida Department of Transportation
Georgia Department of Transportation
Illinois Department of Transportation
Indiana Department of Transportation
Kentucky Transportation Cabinet
Louisiana Department of Transportation
Maine Department of Transportation
Maryland Department of Transportation
Massachusetts Department of Transportation
Michigan Department of Transportation
Minnesota Department of Transportation
Missouri Department of Transportation
Nevada Department of Transportation
New Hampshire Department of Transportation
New Jersey Department of Transportation

New York Department of Transportation
North Carolina Department of Transportation
Ohio Department of Transportation
Oklahoma Department of Transportation
Oregon Department of Transportation
Pennsylvania Department of Transportation
Rhode Island Department of Transportation
South Carolina Department of Transportation
Tennessee Department of Transportation
Texas Department of Transportation
Vermont Agency of Transportation
Virginia Department of Transportation
Washington State Department of Transportation
Wisconsin Department of Transportation

Regional and Nationwide High-Speed Rail Associations and Agencies

California High-Speed Rail Authority
Florida High Speed Rail
Indiana High-Speed Rail Association
Midwest High-Speed Rail Association
Southeast High-Speed Rail Corridor
US High Speed Rail Association

Engineering and Consulting Firms

Fehr & Peers
HNTB
Kittelson
Parsons Brinckerhoff
PBSJ

National Agencies

America 2050
APTA Center for High-Speed Rail
Federal Railroad Administration

A.2. Survey

Page 1 – Opening Letter

Dear Sir or Madam,

My name is Dominik Ziemke. I am a graduate student in Transportation Systems Engineering under the supervision of Dr. Michael D. Meyer at the Georgia Institute of Technology.

In partial fulfillment for my Master’s Degree I am writing a thesis entitled

“High-speed rail systems for the United States”.

My thesis will incorporate a comparison of different high-speed rail systems and their applicability in the United States. As a basis for the evaluation of different high-speed rail systems, I would like to know how agencies and organizations that are (or might in the future be) concerned with passenger rail rank the importance of different points of comparison.

That is why I would like to ask for your assistance in building an information base for my research.

The following pages contain a survey that I would like to ask you to fill in. Completing this survey should take no more than 15 minutes. Of course, the survey assures anonymity – the results will only be returned in an accumulated way.

If there are any questions, please feel free to contact me at:

Dominik Ziemke
Graduate Student in Transportation Systems Engineering
School of Civil and Environmental Engineering
Georgia Institute of Technology
790 Atlantic Drive - Atlanta, GA 30332
email: ziemke@gatech.edu
phone: 404-916-5974

I would like to thank you in advance for your participation. If you could fill in the survey this or the next week (by Friday, June 4th) I would be particularly grateful.

Of course, I will be more than happy to provide you with the results of my research after the completion of my work.

Sincerely,
Dominik Ziemke

Page 2 – Guidance

In the following survey, I will be asking you to rate different features within the categories

Environmental Aspects
Economical Aspects
Aspects of User Friendliness
Technical Aspects
Political Aspects
Operational Aspects
Safety Aspects

in terms of their importance. This should represent your appreciation of strengths and weaknesses of the features on the following pages.

The values you will be assigning do not have to perfectly match the text descriptions (e.g. "very important"). Since the results will be normalized later, the RELATIVE IMPORTANCE between the different features is most important.

The survey does not require you to assign values of importance to every single feature. I would ask you, however, to assign values of importance to as many features as possible.

Page 3 – Environmental Aspects

The below criteria are all part of the category "Environmental Aspects". Please determine for each criterion how important you consider it when comparing different high-speed rail systems in terms of environmental aspects.

Note: The values you assign do not have to perfectly match the text descriptions (e.g. "very important"). Since the results will be normalized later, the RELATIVE IMPORTANCE between the different features is most important.

Table 99: Raw Survey Data for Environmental Aspects

	Unimportant (0)	Hardly Important (1)	Somewhat Important (2)	Important (3)	More Important (4)	Very Important (5)	Extremely Important (6)	Responses
Energy Consumption	0.0% (0)	0.0% (0)	9.1% (2)	18.2% (4)	18.2% (4)	40.9% (9)	13.6% (3)	22
Noise Emissions	0.0% (0)	0.0% (0)	4.5% (1)	40.9% (9)	27.3% (6)	27.3% (6)	0.0% (0)	22
Interference with the Natural Environment (Water, Animals, Plants)	0.0% (0)	0.0% (0)	4.5% (1)	36.4% (8)	13.6% (3)	27.3% (6)	18.2% (4)	22
Suitability for Co-Alignment with other Transportation Infrastructure (e.g. Interstate Highways)	0.0% (0)	0.0% (0)	9.1% (2)	45.5% (10)	18.2% (4)	9.1% (2)	18.2% (4)	22
Need for Construction of Structures (Bridges, Tunnels)	0.0% (0)	0.0% (0)	4.5% (1)	18.2% (4)	45.5% (10)	22.7% (5)	9.1% (2)	22
Visual Division of Landscape / Cityscape	0.0% (0)	9.1% (2)	13.6% (3)	50.0% (11)	13.6% (3)	13.6% (3)	0.0% (0)	22
Divisive Effect (Physical Separation of Landscape / Cityscape)	0.0% (0)	9.1% (2)	18.2% (4)	31.8% (7)	27.3% (6)	9.1% (2)	4.5% (1)	22
Land Consumption	0.0% (0)	0.0% (0)	27.3% (6)	27.3% (6)	27.3% (6)	18.2% (4)	0.0% (0)	22
Vibration	0.0% (0)	9.5% (2)	9.5% (2)	47.6% (10)	19.0% (4)	14.3% (3)	0.0% (0)	21
Material and Resource Consumption	0.0% (0)	4.8% (1)	9.5% (2)	42.9% (9)	19.0% (4)	23.8% (5)	0.0% (0)	21
Electromagnetic, Magnetic, and Electric Fields	0.0% (0)	4.8% (1)	23.8% (5)	38.1% (8)	19.0% (4)	14.3% (3)	0.0% (0)	21
Pollutant Emissions (e.g. Greenhouse Gases)	0.0% (0)	4.5% (1)	0.0% (0)	31.8% (7)	9.1% (2)	31.8% (7)	22.7% (5)	22

Page 4: Economical Aspects

The below criteria are all part of the category "Economic Aspects". Please determine for each criterion how important you consider it when comparing different high-speed rail systems in terms of economic aspects.

Table 100: Raw Survey Data for Economic Aspects

	Unimportant (0)	Hardly Important (1)	Somewhat Important (2)	Important (3)	More Important (4)	Very Important (5)	Extremely Important (6)	Responses
Investment Costs	0.0% (0)	0.0% (0)	0.0% (0)	18.2% (4)	9.1% (2)	45.5% (10)	27.3% (6)	22
Maintenance Costs	0.0% (0)	0.0% (0)	0.0% (0)	4.5% (1)	22.7% (5)	45.5% (10)	27.3% (6)	22
Operation Costs	0.0% (0)	0.0% (0)	0.0% (0)	4.5% (1)	22.7% (5)	36.4% (8)	36.4% (8)	22
Profits	0.0% (0)	9.1% (2)	13.6% (3)	45.5% (10)	9.1% (2)	13.6% (3)	9.1% (2)	22
Ridership Generation	0.0% (0)	0.0% (0)	0.0% (0)	4.5% (1)	9.1% (2)	50.0% (11)	36.4% (8)	22
Chances to Acquire Grants	0.0% (0)	0.0% (0)	4.5% (1)	9.1% (2)	27.3% (6)	36.4% (8)	22.7% (5)	22
Ability to Use Existing Railway Tracks	0.0% (0)	9.1% (2)	4.5% (1)	9.1% (2)	13.6% (3)	45.5% (10)	18.2% (4)	22

Page 5: Aspects of User Friendliness

The below criteria are all part of the category "Aspects of User Friendliness". Please determine for each criterion how important you consider it when comparing different high-speed rail systems in terms of aspects of user friendliness.

Table 101: Raw Survey Data for Aspects of User Friendliness

	Unimportant (0)	Hardly Important (1)	Somewhat Important (2)	Important (3)	More Important (4)	Very Important (5)	Extremely Important (6)	Responses
Travel Time (for a given distance)	0.0% (0)	0.0% (0)	0.0% (0)	9.5% (2)	19.0% (4)	47.6% (10)	23.8% (5)	21
Arrival Frequency	0.0% (0)	0.0% (0)	0.0% (0)	4.8% (1)	38.1% (8)	28.6% (6)	28.6% (6)	21
Comfort	0.0% (0)	0.0% (0)	4.8% (1)	33.3% (7)	33.3% (7)	23.8% (5)	4.8% (1)	21
Travel Fare	0.0% (0)	0.0% (0)	4.8% (1)	9.5% (2)	57.1% (12)	23.8% (5)	4.8% (1)	21
Number of Transfers	0.0% (0)	0.0% (0)	9.5% (2)	42.9% (9)	4.8% (1)	28.6% (6)	14.3% (3)	21
Service (e.g. Catering on-board)	0.0% (0)	4.8% (1)	28.6% (6)	38.1% (8)	14.3% (3)	14.3% (3)	0.0% (0)	21
Accessibility of Stations	0.0% (0)	0.0% (0)	4.8% (1)	9.5% (2)	19.0% (4)	52.4% (11)	14.3% (3)	21
Luggage Transportation	0.0% (0)	14.3% (3)	23.8% (5)	28.6% (6)	28.6% (6)	4.8% (1)	0.0% (0)	21
Image and Attractivity	0.0% (0)	0.0% (0)	19.0% (4)	23.8% (5)	33.3% (7)	23.8% (5)	0.0% (0)	21

Page 6: Technical Aspects

The below criteria are all part of the category "Technical Aspects". Please determine for each criterion how important you consider it when comparing different high-speed rail systems in terms of technical aspects.

Table 102: Raw Survey Data for Technical Aspects

	Unimportant (0)	Hardly Important (1)	Somewhat Important (2)	Important (3)	More Important (4)	Very Important (5)	Extremely Important (6)	Responses
Acceleration	0.0% (0)	0.0% (0)	5.0% (1)	45.0% (9)	5.0% (1)	35.0% (7)	10.0% (2)	20
Braking Rate	0.0% (0)	0.0% (0)	10.0% (2)	45.0% (9)	5.0% (1)	30.0% (6)	10.0% (2)	20
Travel Speed	0.0% (0)	0.0% (0)	5.0% (1)	5.0% (1)	40.0% (8)	30.0% (6)	20.0% (4)	20
Wear and Degradation	0.0% (0)	0.0% (0)	15.0% (3)	15.0% (3)	40.0% (8)	15.0% (3)	15.0% (3)	20
Train Weight	0.0% (0)	5.0% (1)	15.0% (3)	45.0% (9)	20.0% (4)	10.0% (2)	5.0% (1)	20
Compactness of Train (i.e. Lower Length, Lower Clearance Height)	0.0% (0)	10.5% (2)	5.3% (1)	57.9% (11)	10.5% (2)	15.8% (3)	0.0% (0)	19
Flexibility in Track Alignment	0.0% (0)	0.0% (0)	5.0% (1)	20.0% (4)	40.0% (8)	25.0% (5)	10.0% (2)	20
Driving Resistance (e.g. Aerodynamic Drag, Rolling Resistance)	0.0% (0)	10.0% (2)	10.0% (2)	40.0% (8)	10.0% (2)	25.0% (5)	5.0% (1)	20
Easiness to Integrate Stations into Cities	0.0% (0)	0.0% (0)	0.0% (0)	19.0% (4)	19.0% (4)	47.6% (10)	14.3% (3)	21

Page 7: Operational Aspects

The below criteria are all part of the category "Operational Aspects". Please determine for each criterion how important you consider it when comparing different high-speed rail systems in terms of operational aspects.

Table 103: Raw Survey Data for Operational Aspects

	Unimportant (0)	Hardly Important (1)	Somewhat Important (2)	Important (3)	More Important (4)	Very Important (5)	Extremely Important (6)	Responses
Capacity	0.0% (0)	0.0% (0)	0.0% (0)	4.8% (1)	28.6% (6)	52.4% (11)	14.3% (3)	21
Reliability (e.g. Independence of Weather Conditions)	0.0% (0)	0.0% (0)	0.0% (0)	9.5% (2)	14.3% (3)	47.6% (10)	28.6% (6)	21
Stopping Time at Stations	0.0% (0)	0.0% (0)	0.0% (0)	38.1% (8)	19.0% (4)	38.1% (8)	4.8% (1)	21
Flexibility in Operation (e.g. Increasing / Decreasing Number of Cars)	0.0% (0)	0.0% (0)	9.5% (2)	23.8% (5)	28.6% (6)	14.3% (3)	23.8% (5)	21
Ability to Create a Connected High-Speed Rail Network	0.0% (0)	0.0% (0)	9.5% (2)	14.3% (3)	9.5% (2)	23.8% (5)	42.9% (9)	21
Achievable Speeds in Urbanized Areas	0.0% (0)	0.0% (0)	4.8% (1)	23.8% (5)	33.3% (7)	28.6% (6)	9.5% (2)	21
Suitability for Varying Distances between Stations	0.0% (0)	4.8% (1)	0.0% (0)	38.1% (8)	19.0% (4)	23.8% (5)	14.3% (3)	21
Integration in Existing Transportation Infrastructure	0.0% (0)	0.0% (0)	0.0% (0)	14.3% (3)	19.0% (4)	28.6% (6)	38.1% (8)	21

Page 8: Political Aspects

The below criteria are all part of the category "Political Aspects". Please determine for each criterion how important you consider it when comparing different high-speed rail systems in terms of political aspects.

Table 104: Raw Survey Data for Political Aspects

	Unimportant (0)	Hardly Important (1)	Somewhat Important (2)	Important (3)	More Important (4)	Very Important (5)	Extremely Important (6)	Responses
Societal Acceptance	0.0% (0)	0.0% (0)	4.8% (1)	14.3% (3)	28.6% (6)	47.6% (10)	4.8% (1)	21
Perceived Technological Maturity	0.0% (0)	0.0% (0)	9.5% (2)	28.6% (6)	19.0% (4)	38.1% (8)	4.8% (1)	21
Potential for Further Development	0.0% (0)	0.0% (0)	9.5% (2)	4.8% (1)	23.8% (5)	38.1% (8)	23.8% (5)	21
Political Feasibility	0.0% (0)	0.0% (0)	4.8% (1)	14.3% (3)	4.8% (1)	61.9% (13)	14.3% (3)	21
External Economic Effects (e.g. Creation of Jobs)	0.0% (0)	0.0% (0)	0.0% (0)	9.5% (2)	28.6% (6)	33.3% (7)	28.6% (6)	21
Suitability to Serve as a Showcase Project	0.0% (0)	0.0% (0)	14.3% (3)	28.6% (6)	19.0% (4)	33.3% (7)	4.8% (1)	21

Page 9: Safety Aspects

The below criteria are all part of the category "Safety Aspects". Please determine for each criterion how important you consider it when comparing different high-speed rail systems in terms of safety aspects.

Table 105: Raw Survey Data for Safety Aspects

	Unimportant (0)	Hardly Important (1)	Somewhat Important (2)	Important (3)	More Important (4)	Very Important (5)	Extremely Important (6)	Responses
Risk of Derailment	0.0% (0)	0.0% (0)	0.0% (0)	9.5% (2)	14.3% (3)	19.0% (4)	57.1% (12)	21
Risk of Collisions with other Trains	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)	4.8% (1)	28.6% (6)	66.7% (14)	21
Risk of Collisions with other Modes of Transportation and Environment	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)	4.8% (1)	33.3% (7)	61.9% (13)	21
Safety in Case of Natural Disasters (e.g. Earthquakes)	0.0% (0)	0.0% (0)	0.0% (0)	4.8% (1)	23.8% (5)	38.1% (8)	33.3% (7)	21
Risk of Material Fatigue	0.0% (0)	0.0% (0)	10.0% (2)	5.0% (1)	10.0% (2)	40.0% (8)	35.0% (7)	20
Sensitivity towards Obstructions on Guideway	0.0% (0)	0.0% (0)	5.0% (1)	5.0% (1)	10.0% (2)	30.0% (6)	50.0% (10)	20
Perceived Level of Safety by User	0.0% (0)	0.0% (0)	0.0% (0)	4.8% (1)	14.3% (3)	23.8% (5)	57.1% (12)	21
Easiness to Evacuate Train	0.0% (0)	0.0% (0)	0.0% (0)	5.0% (1)	20.0% (4)	30.0% (6)	45.0% (9)	20

Page 10: Rating of Category Groups

Finally, after you have rated several factors within seven categories, I would ask you to rate the importance of these seven groups of categories as a whole.

Table 106: Raw Survey Data for Rating of Comparison Categories

	Unimportant (0)	Hardly Important (1)	Somewhat Important (2)	Important (3)	More Important (4)	Very Important (5)	Extremely Important (6)	Responses
Environmental Aspects	0.0% (0)	0.0% (0)	0.0% (0)	23.8% (5)	23.8% (5)	28.6% (6)	23.8% (5)	21
Economical Aspects	0.0% (0)	0.0% (0)	0.0% (0)	9.5% (2)	19.0% (4)	38.1% (8)	33.3% (7)	21
Aspects of User Friendliness	0.0% (0)	0.0% (0)	0.0% (0)	19.0% (4)	23.8% (5)	52.4% (11)	4.8% (1)	21
Technical Aspects	0.0% (0)	0.0% (0)	4.8% (1)	19.0% (4)	42.9% (9)	28.6% (6)	4.8% (1)	21
Operational Aspects	0.0% (0)	0.0% (0)	4.8% (1)	9.5% (2)	28.6% (6)	38.1% (8)	19.0% (4)	21
Political Aspects	0.0% (0)	0.0% (0)	5.0% (1)	20.0% (4)	20.0% (4)	55.0% (11)	0.0% (0)	20
Safety Aspects	0.0% (0)	0.0% (0)	0.0% (0)	4.8% (1)	4.8% (1)	28.6% (6)	61.9% (13)	21

Page 11: Missing Criteria of Comparison – Comments

In your opinion, are there any features or points of comparison missing in this survey? If so, please specify them including their rating of importance (on a scale from "0" ("unimportant") through "6" ("extraordinarily important")).

This textbox is reserved for any further comments.

Page 12: Thank you

The survey has been completed.
Please click "DONE" to transmit the survey.

Thank you very much for your participation.

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