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Assessment of CHSST Maglev for U.S. Urban Transportation

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July 2002
Final Report

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OFFICE OF RESEARCH, DEMONSTRATION, AND INNOVATION

Assessment of CHSST Maglev for U.S. Urban Transportation

July 2002

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13. ABSTRACT *(Maximum 200 words)*

This report provides an assessment of the Urban Maglev system proposed by the Maglev Urban Systems Associates MUSA team for application in the United States. The proposed system is the Japanese Chubu HSST Maglev which uses electromagnetic suspension principles based on the attractive forces between the vehicle mounted electromagnets and the iron rail on the guideway for levitation. For propulsion, the system uses a vehicle mounted linear induction motor and a reactive aluminum plate on the guideway.

On the basis of the recent visit to Japan and the technical reports from MUSA and CHSST, the Federal Transit Administration (FTA) team evaluated:

1. The system performance and safety characteristics of the guideway, vehicle, levitation, propulsion, braking, and automated train operation,
2. Environmental aspects, and
3. System costs.

The evaluations focused on the FTA System and the U.S. mandatory requirements. This report identifies the requirements not satisfied in the current CHSST design and operation. Specific recommendations are made for improvements in the CHSST system to make it more suitable for U.S. deployment.

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Note: This report uses technical materials on CHSST Maglev. Readers who intend to use of reproduce the CHSST Maglev materials from this report must seek appropriate permission from CHSST officials.

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Minami, Nagoya
457-0837 Japan

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = 0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg)
= 1.1 short tons

VOLUME (APPROXIMATE)

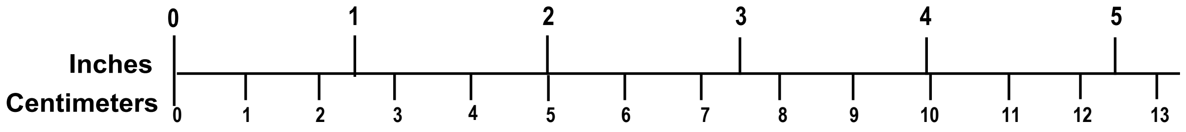
1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)

1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

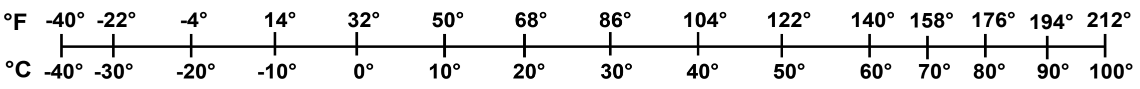
TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION



For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Updated 6/17/98

List of Acronyms

ADA	Americans with Disabilities Act
ATC	automatic train control
ATO	automatic train operation
CHSST	Japanese Urban Maglev system
DC	direct current
EDS	electrodynamic suspension
EMS	electromagnetic suspension
FTA	Federal Transit Administration
EIS	Environmental Impact Statement
LIM	linear induction motors
LRT	Light Rail Transit
LSM	linear synchronous motors
NEMA	National Electrical Manufacturers Association
NFPA	National Fire Protection Association
O/M	operations and maintenance
UTM	Urban Transit Maglev

Table of Contents

List of Tables

List of Figures

Executive Summary

The Federal Transit Administration (FTA) is examining the possibility of introducing magnetically levitated slow speed vehicles (under 160 kph (100 mph)) for urban mass transportation in the United States. Maglev has several advantages over conventional transportation, such as existing automated guideway transits (AGT), Light Rail system, and bus. These include: reduced travel time, congestion mitigation, decreased pollution, reduced noise, increased ride comfort, better grade-climbing capability, improved energy efficiency, reduced maintenance, and possibly, competitive capital, operating and life cycle cost.

The FTA is evaluating a few candidate technologies for application in its Urban Maglev Program. One of the technologies being considered is the Chubu High Speed Surface Transport (CHSST) developed in Japan and proposed by the Maglev Urban System Associates (MUSA). The FTA formed a team of consultants, the FTA Technical Team, to assist in the technical and cost evaluation of the urban maglev projects, including the CHSST Maglev. The team consists of selected technical staff from Foster-Miller, Inc., FL Raposa Services, Thompson Consulting, Inc., and the US DOT/Volpe National Transportation Systems Center. The team visited the CHSST facility and held technical meetings with CHSST and funding agencies for Japanese urban applications. Based on the information gathered during this visit and technical reports submitted by MUSA, the FTA team evaluated the CHSST as presented in this report. Emphasis is placed on how well the CHSST system satisfies the FTA system level performance, safety and cost requirements, and the U.S. mandatory requirements for public transportation systems.

The evaluation led to the following major conclusions:

- The CHSST system is a tested and demonstrated low-speed system that is being readied for commercial application. It is based on mature Electromagnetic Suspension (EMS) technology.
- The CHSST system is intended for operation at 100 kph on the Aichi Prefecture proposed route of approximately 9.5 km in Japan. The system can be run at 130 kph with some upgrades. To reach speeds of 160 kph, a major redesign and development is required.
- The CHSST Maglev is expected to be within safe limits of magnetic and electrical field strengths. Its noise level with its present permissible speed in Japan (100 kph) is reasonably low.
- The system can negotiate 7% gradients, although with significant speed degradation.
- The smaller 100-S vehicle can negotiate 25 m radius curves, but the larger 100-L needs at least a 50 m radius curve.
- The CHSST has zero-speed levitation capability and can stay levitated at the stations, but its levitation gap while running is on the order of 6 mm. All EMS systems are inherently unstable, requiring continuous servo-controlled stabilization of the gap.

- According to the Japanese estimates, it can be cost competitive with Light Rail systems. Similar estimates for U.S. conditions have not yet been made.
- At the present speed limit of 100 kph, the system may find application in the United States. If the system is upgraded and tested at a speed of at least 130 kph, as discussed in this report, it can find application on more urban and suburban routes in the United States.

1 Introduction

The Federal Transit Administration (FTA) has been chartered to perform research and evaluation of Magnetically Levitated train technology (Maglev) for urban passenger transportation in the United States. This mode of transportation in some U.S. cities can compete with conventional transportation modes (such as light rail, monorail, bus) under certain circumstances. Maglev can bring several socioeconomic benefits which include:

- Ride comfort,
- No pollution in congested cities,
- Quiet operation,
- Ability to transport a large number of people at a rapid rate, and
- Shortened trip time with reliable schedules

This can result in improved business activity, increased job opportunities in urban areas, and less dependency on foreign oil.

Maglev technologies are being deployed in other countries, i.e., Japan, Korea and China. The U.S. needs to make a decision on Maglev transportation to reduce traffic congestion and pollution in cities, whose problems may not improve with the use of additional conventional modes of transportation

The FTA has selected candidate Maglev technologies and concepts for evaluation and possible application in the U.S. One of the selected technologies comes from Maglev Urban System Associates (MUSA). This a consortium of the following firms:

- Earth Tech, Inc.,
- Chubu HSST Development Corporation,
- Kimley-Horn Associates,
- Chamberlain Engineering, Inc., and
- Delon Hampton & Associates.

To date, MUSA submitted three technical reports to the FTA on their proposed technology which is based on the Japanese HSST Maglev system. The levitation for the HSST cars is produced using electromagnets on vehicles attracted to steel rails on the guideway. The propulsion force is obtained from a vehicle-borne linear induction motor which utilizes reaction force from aluminum plates attached to the steel rails on the guideway. The levitation gap is continuously monitored by gap sensors and is actively controlled via current supply to the electromagnets on the vehicles.

The FTA sent a delegation to Japan in March, 2002 to experience, understand, and assess the HSST technology. The delegation consisted of the authors of this FTA report and the MUSA team. During the visit with HSST and other staff in Japan, technical reports and papers were collected, including a major report [1] prepared by the Japanese Aichi Prefecture local government in 1993 which provides extensive technical passenger demand, and economic analysis of the system. Based on these and the three technical reports [2,3,4] submitted by the MUSA team, the FTA team prepared this report with an overall objective assessment of the CHSST (Chubu HSST) technology as proposed by the MUSA team.

1.1 Objectives of Report

The specific objectives of the technical report are:

1. Evaluate the CHSST Maglev system on the basis of information gathered during the visit to the demonstration site at Nagoya, Japan, technical interaction with the HSST staff, HSST manufacturers, Japanese government organizations, and the three reports by MUSA to the FTA. Specific components include the following:

   - Guideway,
   - Vehicle levitation and guidance,
   - Propulsion and power,
   - Braking,
   - Automatic train operation,
   - System safety, and
   - Costs.

   Assess the degree of maturity of the technology, availability of reliable technical data and promise of the technology for U.S. Maglev applications.

2. Specify the FTA system requirements and the U.S. mandatory requirements which are critical to the introduction of the HSST technology in the U.S. Summarize those which are not satisfied in the current practice, or intended use of the HSST technology elsewhere.

3. Identify areas of required improvements and design modifications to make the technology more suitable for the U. S. applications. Identify those areas of design modifications which are reasonably straightforward in the short term, and those which will require development over a long term.

4. Evaluate the system level life cycle costs supplied be the MUSA/Japanese sources. Comment on the cost benefits, if any, over a comparable transportation mode based on conventional technology.

1.2 Report Organization

The report is organized as follows. Chapter 2 is a brief background of the CHSST system. The guideway system, including switches, evaluation and issues, is presented in Chapter 3. The vehicles, including capacity, dynamics and ride quality, is presented in Chapter 4. Chapters 5 and 6 deal with levitation and guidance, and propulsion and power respectively. The braking system and automatic train operation issues are explained in Chapters 7 and 8. Environmental issues are presented in Chapter 9. An outline of performance and safety tests conducted by the HSST and additional tests required for the U.S. application are presented in Chapter 10. System cost evaluation is in Chapter 11, followed by Chapter 12 which presents conclusions and recommendations.

2 Background of CHSST Maglev System

The HSST Maglev system has been in development in Japan for over 25 years, and has evolved through several progressively more practical forms. Fundamentally, the CHSST Maglev utilizes electromagnetic attractive forces between simple dual-pole electromagnets and a steel rail to provide both levitation and guidance. The simplified diagram is shown in Figure 2-1. The upper, or fixed rail, side is a simple steel (iron) section with two downward facing poles mounted on the guideway structure. The lower, upward facing magnet is mounted on the vehicle and is an electromagnet whose intensity is varied continuously by a gap sensor to maintain a constant magnetic gap of approximately 8 mm. This active control is required since otherwise the levitation is unstable. Lateral guidance is provided by the tendency of the electromagnets on the moving train to line up laterally with the poles of the steel guideway. Propulsion and braking is provided by a separate linear induction motor (LIM) system, with the active (energized) side being vehicle-mounted above the same steel rail used for levitation and guidance. There is an additional aluminum plate fastened to the rail top to provide a reaction rail for the LIM. Finally, there are mechanical brakes and landing skids provided on the vehicle which also act on the outer flange and top, respectively, of the basic steel rail section.

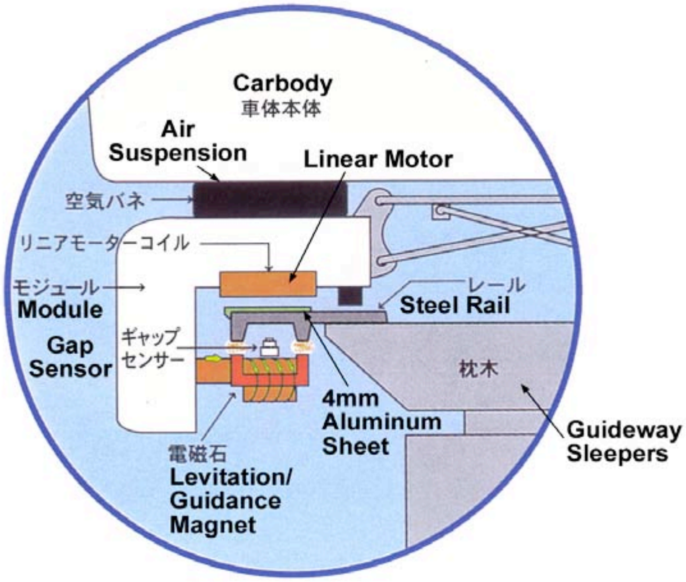


Figure 2-1. CHSST Maglev Rail and Module Cross-Section

2.1 Guideway

The baseline guideway in both the test track and in planned applications is elevated, and comprises a simple box girder for each travel direction topped with transverse steel sleepers, which in turn support the maglev rails described above. The elevated configuration (other than tunnel) is preferred for urban/suburban infrastructure compatibility (Figure 2-2). Two-way elevated guideways comprise the two parallel guideway beams, supported on traditional cross-beams and pylons/footings, designed for local conditions and long-term stability. All services, such as power transmission, signal & communication, etc. are located on the guideway. Rights of way of existing major streets can thus be utilized.

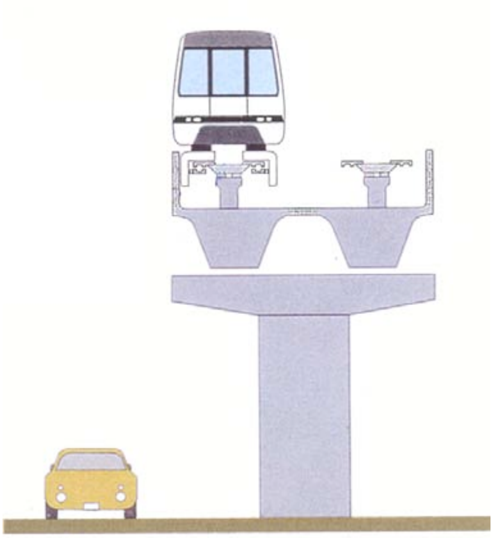


Figure 2-2. CHSST Maglev Elevated Guideway (Walkway Version)

2.2 Vehicle

Pictures of two current test vehicle pairs are shown in Figure 2-3 (a) and (b). The Maglev technology for these two types is essentially identical, each using different numbers of the same basic levitation/propulsion "modules" (the longer 100-L vehicle uses five per side; the shorter 100-S vehicle uses three per side). The vehicles can remain levitated when stopped, such as at a station. Performance can be generally summarized for the current version as having a maximum operating speed of 100 kph, with acceleration and deceleration service rates of 1.1 m/sec^2. Grade climb/descent capability is in the 7 degree range, with horizontal minimum curving radii at slow speeds of 25 m and 50 m for the "short" 8.5 m and "long" 14 m vehicles respectively. These CHSST test vehicles are termed 100-S and 100-L models, and planned deployments would utilize these basic vehicles with updated exteriors, interiors, required equipment, etc. En route 100 m radius turns are negotiated in the 40 kph speed range, with 8 degree cant and net lateral g in-vehicle under 0.1 g. Many other performance and electrical parameters are defined in detailed sections later.

100-L “long” vehicle (2-car consist)
(a)

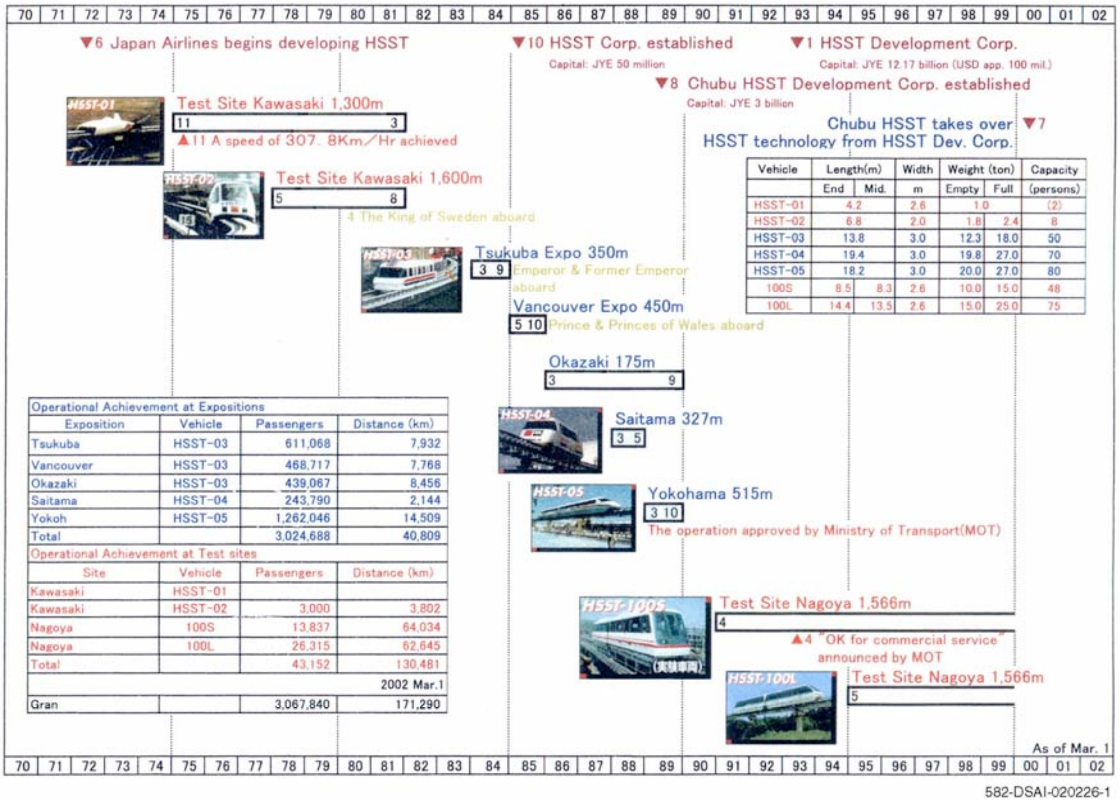
100-S “short” vehicle (2-car consist)
(b)

Figure 2-3. CHSST Maglev Vehicles at Test Track, Nagoya, Japan

The vehicles operate in train-type consists of separate, coupled vehicles. For each configuration, an “A” car (end unit) and “B” car (intermediate unit) are provided. Train length is set by capacity requirements, speed, headway, etc. Two car (A-A) consists operate now on the test track (both 100-L and 100-S vehicles). Manual control is now used, although future versions are planned for automatic operation (ATO). There are systems for speed monitoring, entry/exit from fixed blocks, train protection, communications, etc. which are similar to other transit and monorail systems in Japan and the U.S. System capacity for future applications is set by the familiar combinations of car size, number of cars in consist, minimum safe headways, train control system, acceleration/deceleration/speed profiles, etc. A more detailed discussion of the subsystems and their initial assessment for U.S. conditions are contained in the following Chapters.

2.2.1 Developmental Background

The HSST system was developed in several stages since approximately 1975. A chart depicting this furnished by CHSST is shown in Figure 2-4. This also shows the operating sites (Expositions and Test Tracks) and passengers carried, and distances covered. The passenger-carrying experience has primarily been carried out in the exposition environment over very short single tracks on the order of a few hundred meters to over 1 km long. There, it served as a demonstrator and “people mover”. The experience gained since 1985 is more relevant since the use of elevated guideways started at that time. This is the principal implementation in urban-suburban environments (except for short sections in tunnels for cities, for which the track support is straightforward).



Vehicle	Length(m)		Width	Weight (ton)		Capacity
	End	Mid.	m	Empty	Full	(persons)
HSST-01	4.2		2.6	1.0		(2)
HSST-02	6.8		2.0	1.8	2.4	8
HSST-03	13.8		3.0	12.3	18.0	50
HSST-04	19.4		3.0	19.8	27.0	70
HSST-05	18.2		3.0	20.0	27.0	80
100S	8.5	8.3	2.6	10.0	15.0	48
100L	14.4	13.5	2.6	15.0	25.0	75

Operational Achievement at Expositions			
Exposition	Vehicle	Passengers	Distance (km)
Tsukuba	HSST-03	611,068	7,932
Vancouver	HSST-03	468,717	7,768
Okazaki	HSST-03	439,067	8,456
Saitama	HSST-04	243,790	2,144
Yokoh	HSST-05	1,262,046	14,509
Total		3,024,688	40,809
Operational Achievement at Test sites			
Site	Vehicle	Passengers	Distance (km)
Kawasaki	HSST-01		
Kawasaki	HSST-02	3,000	3,802
Nagoya	100S	13,837	64,034
Nagoya	100L	26,315	62,645
Total		43,152	130,481
			2002 Mar.1
Gran		3,067,840	171,290

Figure 2-4. HSST Development History

The successive vehicles and demonstration sites served to introduce more refined elements of the Maglev vehicles and track, and the current form discussed above is essentially the same as that promoted for deployment applications such as the Tobukyu Line described below. The 1.5 km single-line test track in Oe, a Nagoya suburb, has been in operation for over 15 years developing experience for several vehicle, subsystem and guideway designs.

2.2.2 Potential Deployment in Japan

Reportedly, the technology will be utilized in a 9.2 km / 9-station two-way revenue line in Aichi Prefecture for an Exposition in 2005, which will be known as the "Tobukyu Line". The planned location of this new line will form a "spoke" in the eastern suburbs of the Nagoya area rail network. A layout of the planned line is shown in Figure 2-5, including projected station locations and use of street rights-of-way. It is also intended as a permanent mass transit line. Approximately 7.4 km will use elevated guideway, with 1.8 km in a tunnel at the western end.

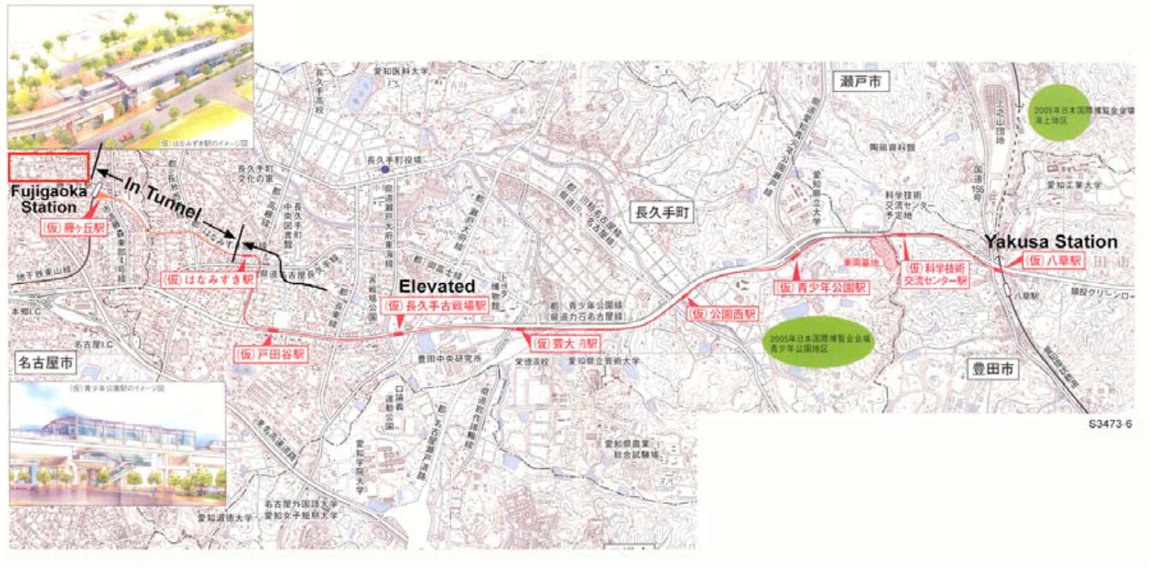


Figure 2-5. Detailed Layout of Tobukyu HSST Line, Aichi Expo 2005

An evaluation and verification/test program for that project was conducted in the 1990-93 time frame leading to approval by Japanese authorities for construction, financing and revenue operation for the public. A detailed report supporting this process [1] gives a description of the evolution, testing, and economic analyses of the systems performed over that period.

Financing is anticipated to come from a combination of prefectural and national governments, plus a consortium of public and private companies participating in various elements of the project construction or operation. Construction has not yet started, although it is planned for sometime in 2003. Currently, construction costs are estimated at about 110 billion ¥ (880 million $) for guideway, stations, power facilities, etc. The unit cost of the elevated section is estimated at 9.1 B¥/km (115 million $/km), with the tunnel section costing three times as much on a unit basis.

The general arrangement is that 40% of the cost will be borne by a combination of private and public companies, and will be recouped in about 20 years. 60% of the cost will be provided by the local, prefectural and national government. The 40% portion also represents the “Maglev” part (active guideway portion, cars, switches, etc.), and the 60% represents the infrastructure (guideway supporting structures, site work, tunnels, etc.). This is diagrammed in Figure 2-6 from their brochure. Revenue is projected to be about 2.8 B¥/yr—90% of which is operating cost and 10% to retire the 40% investment portion above, as shown in Figure 2-4. Carriage of 11 million passengers/year is currently planned for.

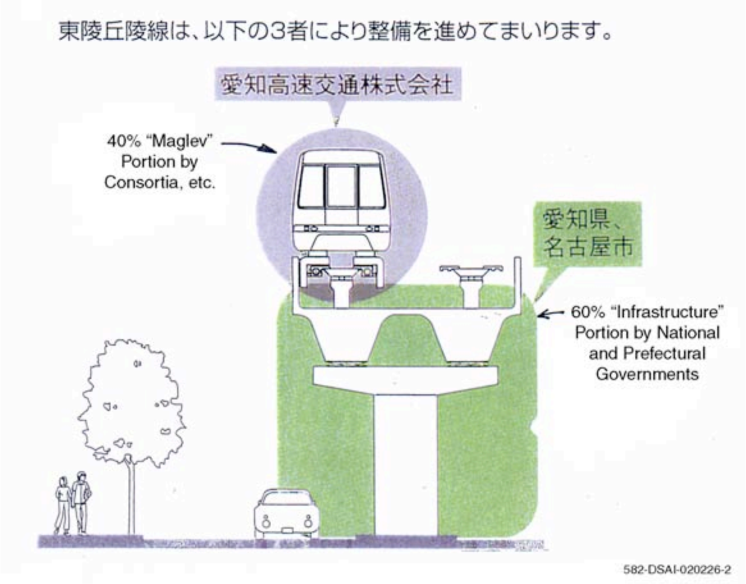


Figure 2-6. Planned Tobukyu CHSST Line Construction Cost Allocation

Several situations in Japan have reportedly slowed the deployment of this system, including the lingering recession, and the high cost of recovery from the destructive Kobe earthquake several years ago. The hope of the government, CHSST and its partners is that the project will go forward as scheduled. However, it is likely to be several years before significant operating experience in the revenue/transportation link setting will be obtained, which may highlight both the advantages and problems of this system. The level of technology is matured, which could be considered as lowering the risk of deployment.

2.2.3 Potential for U.S. Application

The CHSST system is a matured Maglev, reasonably ready for urban transportation applications in the U.S. It does not satisfy certain FTA system and U.S. mandatory requirements as discussed in the following chapters. If deployed in the U.S. with some modifications indicated in this report, it can provide a good starting point for the U.S. to evaluate the benefits of Maglev technology over conventional urban transportation systems, such as light rail and bus. At this moment, however, it is unknown whether the CHSST technology will prove to be more cost effective than the conventional systems or how well it will compete with other emerging Maglev technologies.

3 Guideway System

3.1 Construction Features

The arrangement of the basic guideway beam, rails, sleepers, and support is shown in Figure 3-1. A picture of this guideway as installed at the test track is shown in Figure 3-2. The steel rail section, specially designed, provides both the levitating two-pole lower section and the upper LIM surface, covered with aluminum (insulated from steel), with the outer vertical flange also used for mechanical brakes. Guideway rail alignment can be done via adjustments in the seating of the sleepers on the beams, shown in the view in Figure 3-3. Lines in tunnel are also anticipated, using the sleepers on slab foundation. Little or no at-grade operation is projected in the urban-type infrastructure. Pre-stressed concrete is used for the generic girders of 20 m span on the test track, although steel in special situations has also been used. The test track uses single guideway, but for two-way lines, the two girders will be supported by a conventional transverse concrete cap beam on either single or double pylons, depending on the street layout below. Conventional footings, or piles down to stable bed are used where needed, with control of settlements an important objective. A diagram of various elevated configurations, and one tunnel are shown in Figure 3-4.

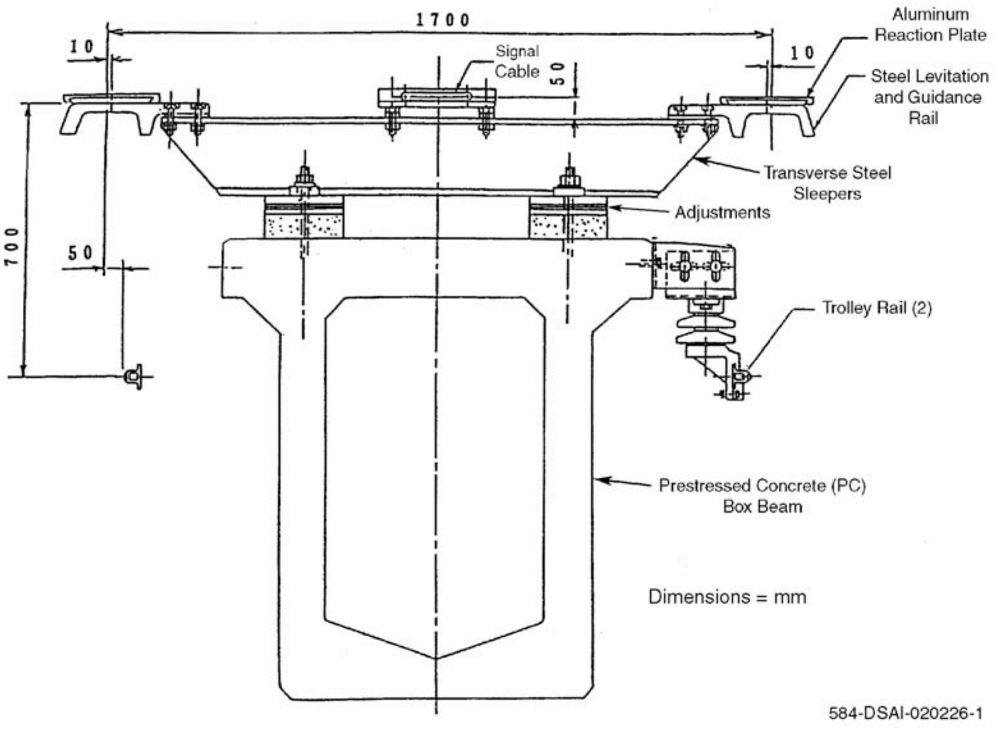


Figure 3-1. Cross Section of Standard CHSST Single Guideway

Figure 3-2. Overall View of Guideway at Test Track

Figure 3-3. Guideway Rail and Sleeper Supports

The steel sleepers are spaced at 1.2 m (4 ft, as seen in a longer view in Figure 3-5) and provisions for alignment are provided at the sleeper-to-main beam connections, and (for gage adjustments), at the rail-to-sleeper connection. Thus the guideway is of "open" construction which aids in preventing an accumulation of snow or water.

The guideway contains two exposed 1500 VDC power rails, one on each side of the box beam below the vehicle modules, as shown in Figure 3-6. Protection measures for any personnel near these rails would have to be taken in a U.S. revenue setting. Power takeoff is via sliding or roller contacts. All communications and train control services are located in a separate conduit down the guideway center on top of the sleepers. This can be seen in Figures 3-2 and 3-5. Other track services can also be included between the rails as seen in Figures 3-2 and 3-5.

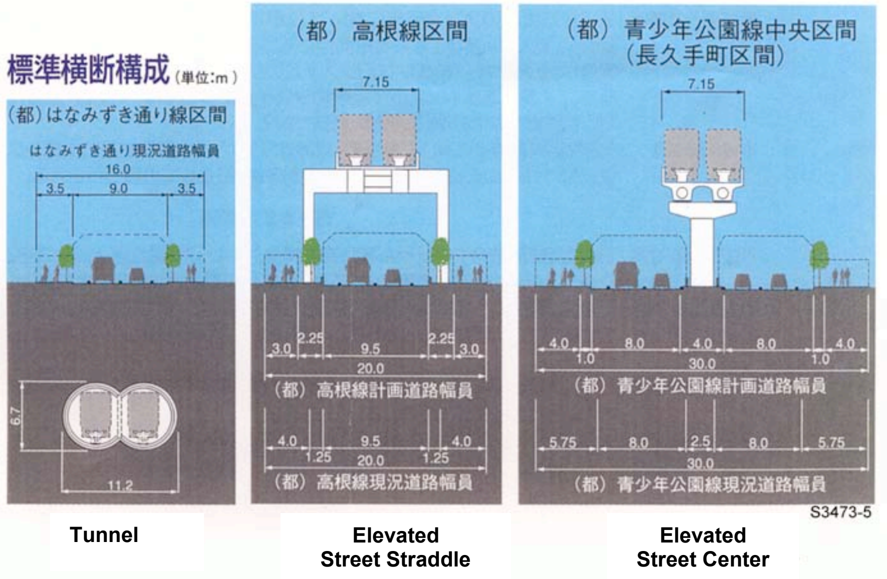


Figure 3-4. Guideway Cross Sections for Tunnel and Elevated Sections

Figure 3-5. Sleeper Spacing for Guideway Rails

Figure 3-6. Side of HSST Guideway--Levitation Rail Above & Trolley Rail on Side

3.2 Design Basis

The elevated version of the guideway utilizes conventional pre-stressed PS concrete girders, in simple spans, topped by transverse steel sleepers which in turn support the maglev rail sections. The design basis for spanning the supporting columns was not specifically presented in the information available to us. A generic pylon support spacing of 20 m is used on the Oe test track, but would vary in specific applications.

According to CHSST staff, the design calculations are based on a modified dynamic mathematical model originally formulated by Prof. Janeway. The main girders need to be designed on the basis of a peak dynamic load anticipated in the service life, considering the additional effects of a degraded guideway condition such as loss of rail support, out-of-tolerance rail, etc. These loads should be evaluated by the model with the complete vehicle-guideway interaction included via modeling of the magnetic and secondary suspensions, vehicle and guideway deformations, damping, etc. The vehicle/consist speeds, weight, support settlements etc., are also important constituents of this evaluation, which should be provided in detail for any projected new application.

The assumed factors of safety, in turn, need to be viewed in the light of the severity of the consequences of failure, such as would be found as one product of a failure modes and effects analysis (FMEA). A ranking of failure severity associated with each proposed factor of safety should be used. Example: a guideway beam collapse during vehicle operation could be the highest severity, while an stable increase of lateral rail misalignment within the maximum permitted would be a much smaller severity.

We would like to see the following design analysis performed for the CHSST guideway structural system, in particular the elevated configuration:

- Earthquake dynamic loading simulation, considering the complete guideway system plus moving and stopped vehicles.

- Adequate structural strength for the full spectrum of loads encountered in both service and in extreme environmental, degraded, and accident-type conditions

- Adequate structural stiffness in all modes considering the interaction of the vehicles and dynamic environmental conditions, to prevent unforeseen dynamic interactions, amplification of loads, and high- and low-cycle fatigue.

- Adequate fatigue life of the guideway including its major components such as rail, attachments, structural members and any other hardware in which a premature failure could cause a problematic or dangerous situation in the maglev system operation.

- Stability in guideway alignment, especially considering foundation and soil conditions. Settlements and tilts of the elevated guideway on pylons or piers obviously is undesirable when a stringent alignment accuracy in the 3-5 mm range is required for normal operations.

- Adequacy in other environmental conditions, such as distortions in heat/cold extremes, snow/ice control and corrosion/pollution deterioration must also be addressed and controlled.

As a part of the design, we would like to see cost considerations based on intelligent tradeoffs among beam design, pylon footing/piling design, hardware, maintenance resources, and safety requirements since the guideway and track structure (without services or land) can constitute 40% or more of the total system cost.

3.3 Operational Experience

There have been several sites at which the CHSST system has been erected and operated with passengers carried, summarized in detail in the 1993 Report [1] and shown previously in Fig. 2-3. There have been at least three sites, each comprising a single guideway section approximately 300 m long, for which operations in an Exposition-type setting have been conducted for several months at a time. At each site, the number of trips ranged from several thousand to over 30,000. However, these various site operations used both at-grade and elevated guideway designs, and these latter differed in construction details.

The 1.5 km test track in Oe, a Nagoya suburb, has been in operation for over 15 years collecting experience for several vehicle, subsystem and guideway designs. A view including vertical and horizontal curves is shown in Figure 3-7. An endurance test using the 2- vehicle 100-L consist was run from December 1995 through March 1999, in which 27,500 trips on the 1.5 km Oe guideway were run, and a record kept of system failures and repairs [4]. One of the 17 failures reported was a de-levitation due to a weak rail structure; it is not known if this was a fastener, rail or sleeper failure. (The test track contains approximately 300 10 m-long rail sections and 1250 steel sleepers.)

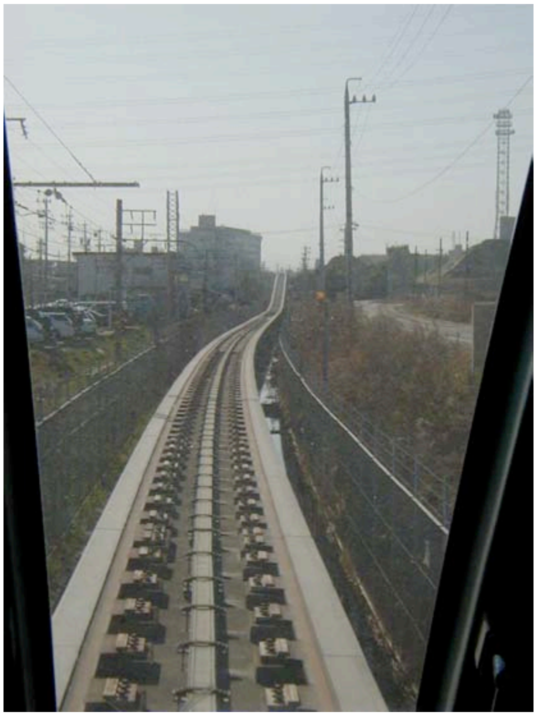


Figure 3-7. Test Track Guideway Section with Horizontal and Vertical Curves

The test track guideway was also used to perform many experimental tests of guideway performance and function, as explained in the 1993 Aichi Prefecture report in Ref. 1. The topics covered are summarized in Table 3-1 below, using their numbering system for ease of reference:

Table 3-1. Test and Experimentation Documentation for CHSST Guideway in 1993 Report [1]

2.1 Establishment of design load condition

2.1.1 Measurement of displacement and girder strain from the weight of fully loaded car
2.1.2 Measurement of displacement and girder strain from fully loaded car running at constant speed to determine impact load factor
2.1.3 Measurement of displacement and girder strain in case module of fully loaded car fails to levitate
2.1.4 Measurement of displacement and girder strain in case of fully loaded car skidding (sliding) on the rail
2.1.5 Measurement of displacement and girder strain caused by temperature change
2.1.6 Measurement of strains of girder by the vehicle moving to start
2.1.7 Measurement of strains of girder by the vehicle braking
2.1.8 Measurement of strains of girder by centrifugal force from the vehicle running along curved rail failure

2.2 Guideway structure

2.2.1 Examination of stress on experimental guideway structure components
2.2.2 Inspection of rail after 2 years of operation
2.2.3 Measurement of peculiar vibration frequency of experimental guideway structure
2.2.4 Examination of girder deflection conditions
2.2.5 Examination of allowed limits for guideway accuracy
2.2.6 Determination of maintenance method for guideway
2.2.7 Investigation of guideway maintenance car
2.2.8 Comparison of HSST construction cost with that of other systems
2.2.9 Investigation of most suitable guideway structure for HSST system by means of train running tests

2.3 Switching

1.3.1 Function test of switching accuracy and turn-out time
1.3.2 Confirmation of vehicle running characteristics on switching track
1.3.3 Endurance test of switching track
1.3.4 Measurement of stress in switching components

Some conclusions from these tests were presented in the original report [1], although detailed results are not shown in this report. It will be useful to have specific recommendations from CHSST on how the structural integrity of the guideway should be monitored. It can be done either using a permanent set of sensors located along the guideway, or by means of a specially instrumented inspection car deployed daily ahead of scheduled runs to evaluate and ensure that the guideway irregularities and any other conditions are within allowable limits. This is important in view of the stringent guideway tolerances, which are discussed later.

Another important aspect not apparently covered in the tests is the guideway/component fatigue or endurance test which is discussed later.

3.4 Performance Characteristics

The key performance characteristics of the guideway, other than the structural code requirements which must be met, are (a) the adequate bending stiffness to control dynamic coupling with the vehicles and verification of the actual stiffness vs. calculated, (b) deflection performance of the guideway, and (c) the control of thermal distortions which can cause excessive deflections. Each have had some limited testing performed as shown above in Table 3-1.

(a) Adequacy and verification of bending stiffness

The guideway beam stiffness was measured by determining the fundamental beam bending frequency for the standard 20 m simply-supported beam w/guideway components attached. (This was in the region of 5 Hz). We first wanted to confirm that this frequency was high enough to be comfortably above the stimulation caused by the passage of consists over the beams, deflected between pylon supports. This is termed the passing frequency, as diagrammed in Figure 3-8.

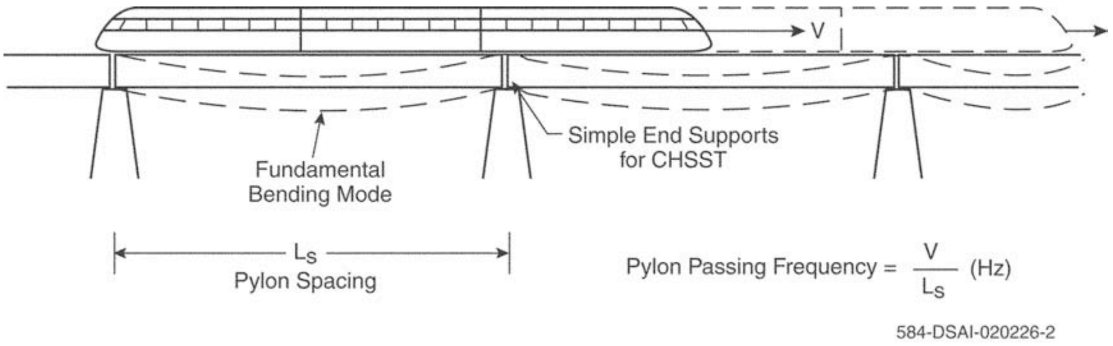


Figure 3-8. Vehicle Pylon Passing Frequency (vs. Fundamental Guideway Beam Bending Frequency)

A simple analysis shows how maintaining the stiff/mass ratio (EI/m) well over the passing frequency insures this. It is assumed for lower speed Maglev applications that the fundamental beam bending frequency can be designed to be well above the maximum vehicle pylon passing frequency. This assures low levels of coupling and hence conservatively low dynamic load factors. Figure 3-9 shows the relationship of the beam frequency vs. the passing frequency, where it can be seen that such beams would likely be stiff enough even for travel speeds of 160 kph (100 mph) which is the FTA speed requirement.

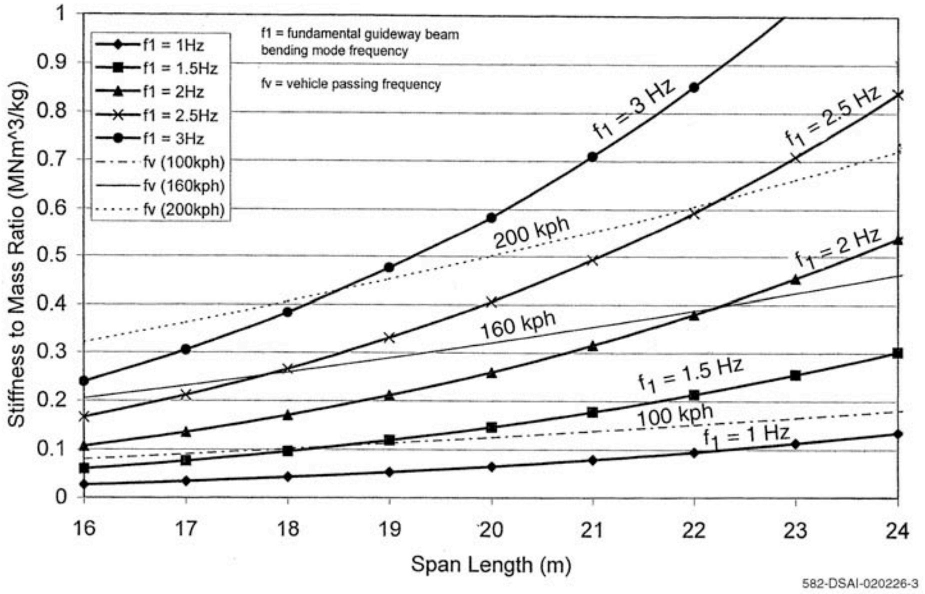


Figure 3-9. Relationship of Beam Bending Frequency vs. Vehicle Passing Frequency

What appears to be a conservative stiffness from this dynamic point of view seems to justify the MUSA contention that the factors of safety/dynamic load factors for the basic code analysis can be reduced from 1.6 to 1.3 (other sections use different ratios but the rationale is the same). This is based on the beam frequency being 3x the passing frequency at 100 kph. However, the final product would require that a satisfactory dynamic model, with the actual train/car weights and the maximum possible irregularities be made available showing how ride quality and safety considerations would always be met. The dynamic measurements quoted in [1] were apparently only for the design maximum irregularities (6mm range in center span) so the dynamic load factors were very low—under 1.1 (in their report, a number of .05 or .06 was expressed as an adder to 1.0—therefore equivalent to a multiplier of 1.05 or 1.06, etc.). This would be used to re-evaluate stiffness/speed margins for higher speeds such as 130 kph, or even 160 kph.

The structural limit loads from U.S. building code type analyses (combining wind, earthquake, etc. into various ultimate load capacities with safety factors) is also an important issue which should be addressed in any submission for construction in the U.S.. For the very high speed maglev systems, the required guideway stiffness (for dynamic load factors) rather than strength generally governs the structural design of the beams. For this low speed application, however, the dynamic stiffness required is relatively lower so either type of requirement (strength or stiffness) could govern.

(b) Deflection performance of the guideway

An issue needing resolution is the CHSST reference to deflection tests on selected beams of the test track. The claim is that with the static loading of the vehicles, deflections are on the order of L/1500, so for a 20 m long beam, deflection would be 13 mm, or approximately _ inch. Camber of the guideway is mentioned, but how it is considered is not clear. The consistency of this value relative to the dynamic conditions tested should be explained, since it appears that the deflection from this test is larger (by a 2x factor) than what would be allowable for gap variations and ride comfort tests.

(c) Guideway Construction and Operating Tolerances

The maglev guideway must be constructed and maintained to a high degree of accuracy for safe and comfortable vehicle operations. These tolerances have been summarized by CHSST and MUSA in Table 3-2 below. They are reportedly appropriate for the 100 kph present maximum operating speed, and would obviously be re-evaluated for higher speeds. Possibly the degree of any curve being negotiated, and the limit speed at those locations, would also require examination of these tolerances. It should be noted that these tolerances should represent a “stack up” of likely irregularities from different sources, such as: static irregularity; thermal/environmental distortion, uncompensated settlements, etc.

Table 3-2. Guideway Tolerance Table (Provided by CHSST/MUSA)

	Tolerance at Construction	During Operation	Remarks
A. Irregularity Deviation from Alignment (Versine)	3 mm (0.12 in.)	5 mm (0.2 in.)	Lateral and vertical deviation from alignment for any 10 m (32.8 ft) chord
B. Track Gauge (1.7 m)	3 mm (0.12 in.)	5 mm (0.2 in.)	Distance between right and left rail centers
C. Rail Joint Alignment	1 mm/1 mm (0.04 in.)	1 mm/1.5 mm (0.04 in./0.06 in.)	Vertical/lateral steps
D. Level Difference	3 mm (0.12 in.)	5 mm (0.2 in.)	Difference between right and left rail levels (relative to any design track cant)

There is a set of smaller tolerances for construction (initial alignment standard) and a larger set representing maximum allowable tolerances. Even these latter are still small, being 5 mm (0.2 in) for vertical or lateral deviation from a sliding 10 m chord reference, and also for gauge variation. Depictions of these different tolerances are shown in Figure 3-10a through 3-10d.

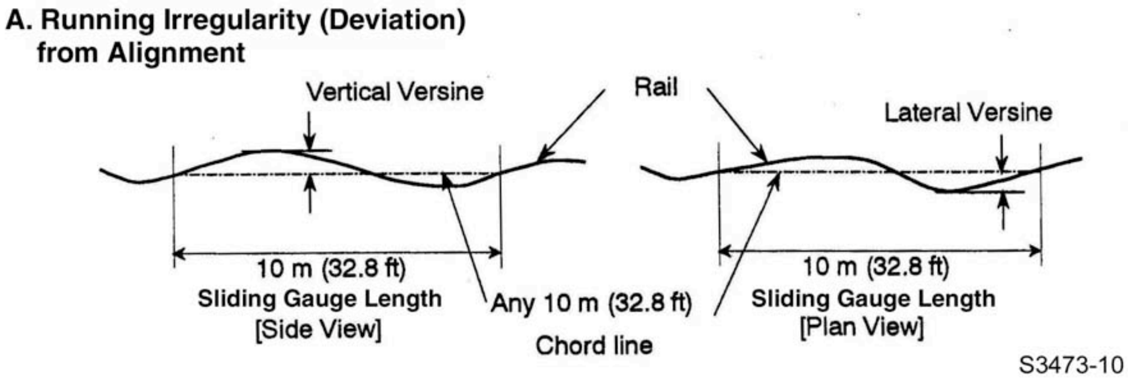


Figure 3-10a. Allowable Guideway Tolerances (Provided by CHSST/MUSA)

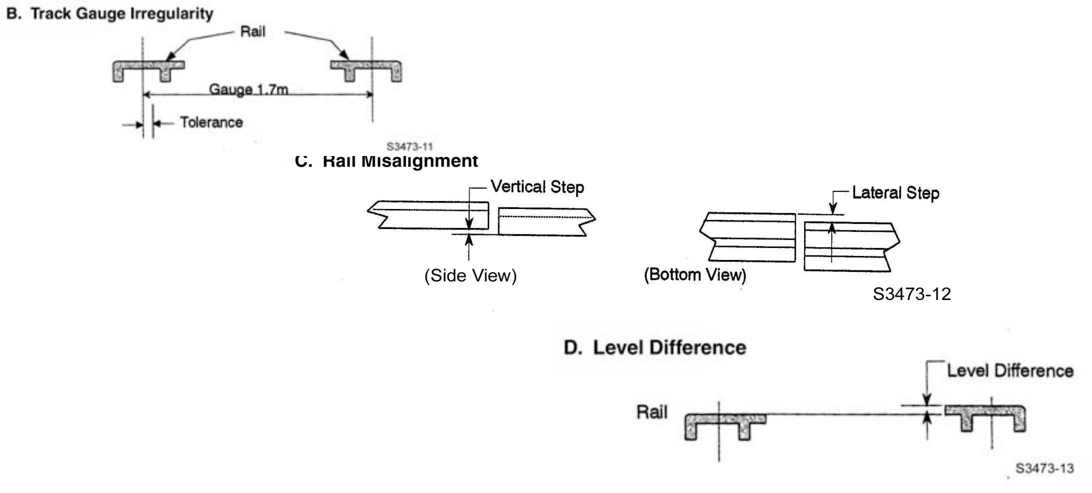


Figure 3-10 b, c, d. Allowable Guideway Tolerances (Provided by CHSST/MUSA)

Past testing has been performed for these type of deviations, but the test cases for which information has been provided to date do not replicate these values. For example, there was test data furnished for the 100-S vehicle moving over a 2mm lateral deviation at 100 kph (we believe for one rail, making it a gage variation), and the vehicle loads and stability were confirmed. This is smaller than the stated maximum allowable in Table 3-2. Likewise, there was a similar test of a vertical “cusp” of 7 mm for the track over one pylon (unclear whether the one pylon was higher or lower) which showed that the dynamic gap variations were acceptable. For the sliding 10m gauge length on 20 m spans, this would represent a “versine” irregularity of 3.5 mm, again less than the stated maximum allowable in Table 3-2. Therefore some clarification is required if larger irregularities have been used in the tests. If not, testing should confirm satisfactory vehicle behavior for the maximum irregularities, consistent with maintenance and inspection strategy.

Clearly the tolerances are stringent and to control these in revenue operations, continuous monitoring and frequent maintenance of the guideway may be required, particularly in poor soil conditions and earthquake prone zones. Such a scenario will be similar to the present U.S. railroads who would like to spend minimally on maintenance, unlike in Japan where this problem is viewed differently. Some proponents of Maglev in the U.S. do perceive the system as requiring least maintenance.

(d) Thermal and Environmental Distortions

The major potential for a high-tolerance structure like the maglev guideway is for transient thermal distortions to add to the “error budget” for overall allowable irregularities. A study by Foster-Miller in 1993 on Transrapid steel guideway showed significant transient deflections due to uneven heating [5] .The CHSST item 2.1.5 above refers to measurements taken in “springtime”, presumably of track deflections. Track was in the unloaded state. However, no results were given and it would be necessary to know for projected U.S. conditions, in which climate is more extreme, what transient deflections could be expected with high sun loading. This is likely to be less of an issue for the CHSST concrete guideway design due to a lower thermal expansion coefficient relative to all-steel. However, there are circumstances when this issue is important, which include:

- Special guideway steel sections, such as used on some curves, switches, and long-span crossings; and
- The steel rail (topped with aluminum sheet) exposed to sun, but broken into 10 m-long sections.

Stiff bolted connections at the joint sleeper, however, could induce some continuity and potential for thermal buckling (hot) or cracking (cold). In the U.S., rail temperatures can easily reach +140º F and -20º F, so some provision in the bolted rail joints can be made to minimize excessive rail axial (tension or compression) forces.

Also, for any direct fixation configuration of CHSST (no sleepers; rail directly fixed to guideway beam), the issues of both thermal bending and excessive rail force become of greater concern and must be considered in the tradeoffs.

(e) Fatigue Life and Detail Mechanical Features

The structural beams and components, especially those unique features to the CHSST maglev such as the rails and attachments to the guideway structure are subjected to fatigue loading situations, both from passage of trains, individual magnets, and load combinations such as oscillations from at- or out-of-tolerance guideway geometry. A fatigue life assessment should be provided, and applicable experience can be included. An example in the case of CHSST could be the overhung rail attachment to sleepers, in which a rail crack or bolt fastener failure would compromise operation. Past experience with the German Transrapid showed that the repeated passing of the individual bogies (not only the consist as a single event) was responsible for fatigue failures in the guideway coil attachments. The rate of failure here accelerated as bolts loosened. The FTA requirement on the guideway life is 75 years. It is important to evaluate the CHSST guideway and its component life.

3.5 Switching

A mechanical segmented switch has also been designed and incorporated into the Oe test track, providing a turnout which also includes a curve of 25 m radius. This is hydraulically operated, with the movable steel guideway sections and track supported by rollers and guides. The 25 m radius guideway section leading into this is shown in Figure 3-11. The switch itself provides a change in direction of 12-15 degrees, with the remainder of the turnout being fixed track. The switch operation is shown in Figure 3-12. Figure 3-13 shows the actual switch as it is moved from the through to the turnout direction. The power rails on the guideway sides are included, having leaf-type contacts in the pivoting areas.

Figure 3-11. 25 m Radius Curved Guideway Leading Into Switch

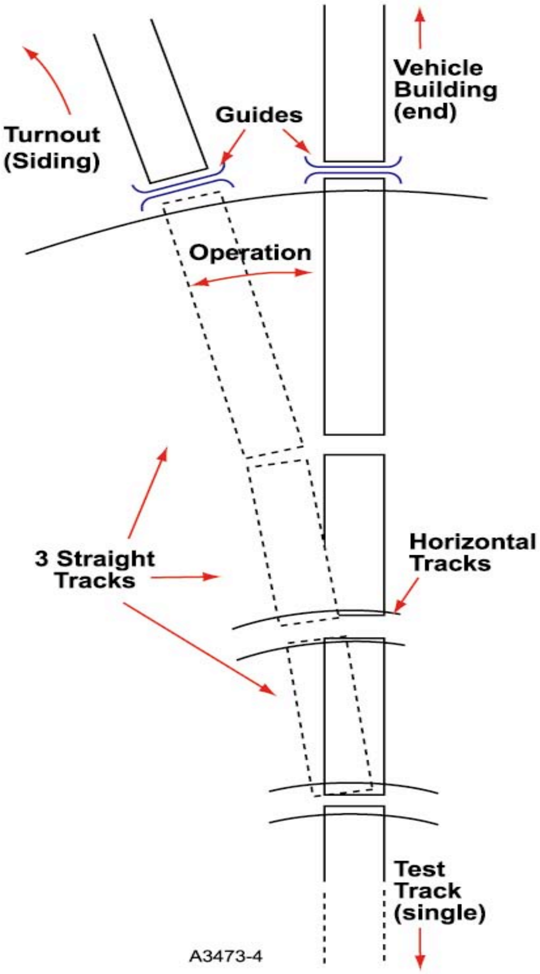


Figure 3-12. CHSST Segmented Switch Operation at Test Track

(a) Through Direction (b) Turnout Position

Figure 3-13. Switch Moved from Through to Turnout Direction

Train speed in the through direction (assuming tangent track) is not limited by the switch. However, since curving negotiation is restricted by mechanical vehicle-to-guideway rail interference as discussed in Chapter 4, these same apply to the switch. Therefore, even for the 8.5 m-long 100-S vehicles, the switch can be negotiated only at low (yard-type) speeds. The three movable sections, progressively longer and totaling approximately 25-30 m could be increased further in length to permit higher turnout speeds. However, the switch becomes bulky, cumbersome and costly.

However, there has been no information yet provided on how such switches would be used in either the new Tobukyu line or other projected applications. While of a straightforward design, the switch is expensive due to the inherent need for the whole guideway structure to be part of the movable sections; this is true for many other systems such as monorail as well. A revenue operating system (as opposed to a demo test track) will have the need for many switches both in yard and en route. For example, if one direction of the guideway is out of service or blocked, switches to the other side (in both directions) would be needed to use opposing track. Also, with maintenance yards, a network of switches to move rolling stock to/from the line is naturally required. Therefore, the size, speed and cost of the switches can affect the physical and economic plan of a system.

Also speed of operation could be an issue, since 15 sec is presently required for full travel. This might affect scheduling where tight headways are needed to achieve high passenger line capacity. All these switching issues become important for potential U.S. application, in addition to improvements in the switch design for function and cost.

3.6 Foundation and Supporting Pylons

The history of the CHSST test track in this regard is good, in that no excessive settlements needing correction have been reported, nor were there any pylon failures. However, the guideway foundation for the test track used piles due to the poor soil conditions. These pile-type foundations, although expensive, were apparently stable for efficient operations. This is a more costly solution than spread footings or mini-piles, which might be tempting for their lower costs in marginal soils. The maintenance plan, safety plan and costs must allow for the effects of settlements or have measures taken to minimize them with up-front investments. Also, the guideway height at the test track is low compared to the potential for revenue lines, where heights of 5-10 m (16.5-33 ft) would be needed especially in more hilly terrain. This would greatly increase movements at track level from settlements (and exacerbate earthquake deflections), so these issues must be addressed in any specific planned deployment.

More data from CHSST is needed on the alignment maintenance activity needed over the years on this guideway. The design-cost tradeoffs for each individual footing system (whether deep piles, mini-piles or spread footing and its area) obviously are interrelated with projected maintenance, as well as with the mechanical provisions (range) allowed for future rail alignment adjustments. (As for highways, it is always tempting to reduce the upfront costs with a minimal design for the foundation structures, and defer higher maintenance consequences for later generations.) Although this approach apparently will not be followed in Japan for the Tobukyu Line, according to the CHSST team and Yahagi Construction Co., care must be taken in a U.S. deployment that a conservative design philosophy in this regard is also followed.

3.7 U.S. Mandatory and FTA System Requirements

3.7.1 Structural Aspects

There is an extensive list of guideway design conditions listed in the MUSA Report [3], delineating the many different structural design conditions to be required in the U.S.. This summary is generally adequate since the overall limit strength, dynamic stiffness and environmental conditions are addressed. (An exception regarding assumed dynamic load factors is discussed below in 3.8). Further, by reference the U.S. AASHTO bridge design code (1996) includes a detailed set of design conditions to be demonstrated by structural analysis. The one condition not directly mentioned in the above references are the FTA wind gust structural condition of 160 kph. Experience with highway bridges, however, has generally found that satisfaction of the code regulations also provides adequate performance for this wind speed as an isolated condition, since the wind loads required for the load combinations are near or at this value.

However, in addition to the U.S. bridge and general building codes used as part of the design requirements, there exists a recommended design procedure for elevated concrete transit guideways including maglev. (This is available from the American Concrete

Institute as Publication ACI 358.1R-92.) Where not duplicated in the AASHTO design practice, these conditions should also be addressed by MUSA CHSST.

3.7.2 Guideway Curves

The curve radii used in the CHSST guideway layout are restricted by the vehicle, specifically the mechanical guideway track clearances and also, at higher speeds, by ride comfort limits. The latter is aided by superelevation (up to 8 degrees for both test track and planned Tobukyu deployment). Horizontal curving is limited by clearances in the mechanical brakes and skids, since mechanical braking uses a floating caliper on the outer flange of the steel levitation/guidance/LIM rail section. Vertical radii are limited by both the module flat lower surface length, and also the vehicle length itself.

Note that as for all small radius curves, the beam construction is a steel sheet fabrication. As radii increase, at some point the intent of CHSST is to transition to pre-stressed concrete (PC) box section beams; however, that radius range has not been established. Note that there is one long-span (40m) crossing in their test track which uses a steel box section, presumably since it is a “one-off” item there.

For vertical curve negotiation, a 1500 m radius limit would normally apply to the longer 100-L cars, and 1000 m to the shorter 100-S car. The longer car is operated on the test track to 1000 m radius but without extra tolerance margins expected for a revenue line. The 1000m vertical curve min radius is an FTA requirement, met by the CHSST. Figure 3-14 shows a test track section with a 1000 m radius vertical curve transitioning to a 7 percent upward grade.

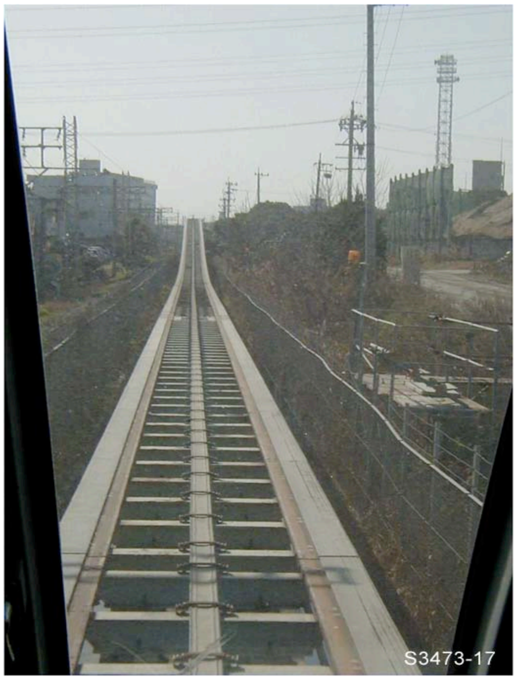


Figure 3-14. Vertical Curve at CHSST Test Track

3.8 Evaluation and Issues

The various aspects of the guideway structural design and performance, as they apply to the CHSST system, have been discussed in the detailed sections above. The following paragraphs summarize the assessments in these various areas.

- Structural safety (code) and ultimate load factors:
  The U.S. codes cited by MUSA [3] do cite an adequate U.S. code approach using the AASHTO highway design approach. This contains many combinations of dead, live, environmental, etc. loads and the multiplying factors for overall guideway strength. We also recommend that the guideway meet parallel requirements cited in the American Concrete Institute Publication ACI 358.1R-92 developed specifically for concrete guideways for any load conditions not repeated in the AASHTO code, and further that those unique load conditions be also applied to special guideway sections manufactured from steel, such as long spans, curves, switches, etc.

- Structural stiffness adequacy:
  The dynamic modeling results should be provided for the full range of conditions that produce dynamic load magnification, including: guideway irregularities at maximum allowable vertical and lateral settlements; off-design vehicle conditions (lost levitation, mechanical suspension failure, etc.) and environmental states (thermal, wind and combinations). Some clarification of the dynamic simulation modeling should be provided for comparison to currently accepted methods, even for the lower ratios of vehicle passing frequencies to fundamental beam bending frequencies currently planned. CHSST has correctly estimated that the present guideway beams (simply-supported 20 m spans on the test track, potentially longer in other applications), would likely be sufficiently stiff for 130 kph operation, but reevaluation would be needed for higher speeds, up to 160 kph (100 mph).

- Thermal Issue
  The potential distortions (lateral and vertical) should be provided for U.S. conditions similar to those used for continuously-welded rail. Transient effects of uneven solar heating should be considered in combination with rail fix, especially in the direct-fixation rail-to-guideway configuration.

- Fatigue Life
  The structural beams and components, especially those unique features to the CHSST maglev such as the rails and attachments to the guideway structure should be subjected to a fatigue life assessment. Life of 75 years for permanent infrastructure (guideway beams, supports, mounting hardware) and half that for the rails and attachments should be taken as the goal. The steel sleepers and hardware can be considered in either category, but for all components replacement costs should be considered in the operating cost assessments.

- Foundation and Pylon Cost
  The past experience has been primarily with foundations comprising deep pile systems to provide high stability in poor surface soils. These are higher in cost than spread footings or mini-piles. Tradeoffs need to be done where the same level of stability and need for realignment can be achieved with these less costly systems where subsurface conditions permit.

- Curved Guideway Cost
  The minimum guideway horizontal and vertical radii are limited by the CHSST vehicle. The basic straight PC guideway beam girder can be optimized for the span, simple end support and stiffness conditions described previously. For the 1000 m radius vertical curves, it is likely that these straight beams can be used since the curvature is less than 2 degrees and so adjustment in the sleeper supports can be made. For horizontal curves, however, as radii diminish, the beam design may transition to a steel box section, and these designs all need to be subjected to the same evaluations as for the basic beam. For larger horizontal radii, use of straight PC beams ("chords") of straight beams may be preferred, as tolerated by the vehicle and local network speeds. This should be confirmed in the cost tradeoffs, considering the greater fabrication expense of curved beam sections. Also, for some longer-span situations, consideration might be given to providing a continuous (negative-moment-carrying) connection with adjacent spans, thereby restoring required stiffness without increasing the basic section.

- Guideway Structural Integrity
  A method of monitoring the guideway structural integrity and daily condition should be identified for revenue service application. An inspection vehicle for detecting foreign objects, track structural degradation, and alignment deterioration will have to be designed. This is particularly important for the CHSST guideway because of its very stringent alignment requirements.

- Switching
  The current switch used on the test track is bulky, cumbersome and apparently expensive. Alternate cost effective designs must be considered for applications in U.S. revenue service.

4 Vehicle Design and System Capacity

4.1 Construction Features

The CHSST 100 vehicle is a semi monocoque structure made up of aluminum plate and fiber reinforced plastic. The vehicle floor, made up of honeycomb panels, carries the longitudinal load from couplers and provides a path for the vertical load from the vehicle modules which support the car body.

The levitation, guidance, propulsion and braking functions on the vehicle are co-located into "module" assemblies below the vehicles, mechanically interconnected with each other and the vehicle body above. These modules are lined up consecutively below the vehicle because the full vehicle length is required for the available magnetic intensities to adequately lift, guide, propel and brake the vehicle. This may be seen in Figure 2-3. Since each of these modules is somewhat less than 3 m long (counting inter-spaces), the vehicle lengths under current use and consideration are multiples of this.

Two sizes of vehicles (100-S and 100-L) have been designed, as indicated in Section 2.2 and summarized in Table 4-1. Both cars have been undergoing testing over the last several years. An adaptation of the 100-L vehicle, in 3-vehicle consists, is currently planned for the Tobukyu Line (Figure 4-1).

Table 4-1. Vehicle Specifications

Characteristic	**100-S Specification***	**100-L Specification***
Vehicle Dimensions	8.5 m long 2.6 m wide 3.36 m high	14.0 m long 2.6 m wide 3.2 m high
Empty Weight	9 tonnes	17.5 tonnes
Maximum Loaded Weight	15 tonnes	28.0 tonnes
* "A" type or end/control vehicle		

The occupied portion of the vehicle bodies follows conventional transit layout: two pairs of side doors and a mixture of transverse and wall seating allowing about 2 standees per one seated passenger (assuming U.S. passenger loading density). A control cab is located at each end of the consist. With 34-36 seats, the 100-L type car could accommodate about 80-85 passengers, including standees, based on transit-type floor layouts and standee density typical for the U.S.

4.2 Structural Design Basis

According to MUSA Report #1 [2], the structural design is based on the maximum load expected in service life with a safety factor of 1.5. Additional safety factors (1.15) are used at fittings, castings, and welds. The static load design is adequate for sizing the

	A Car	B Car	Train
No. of Seats	32+2	36	100+4
Standee (0.3m²/person) *	45	48	138
Standee (0.14m²/person)	97	102	296
Capacity (0.3m²/person) *	79	84	242
Capacity (0.14m²/person)	131	138	400

* Typical for U.S.

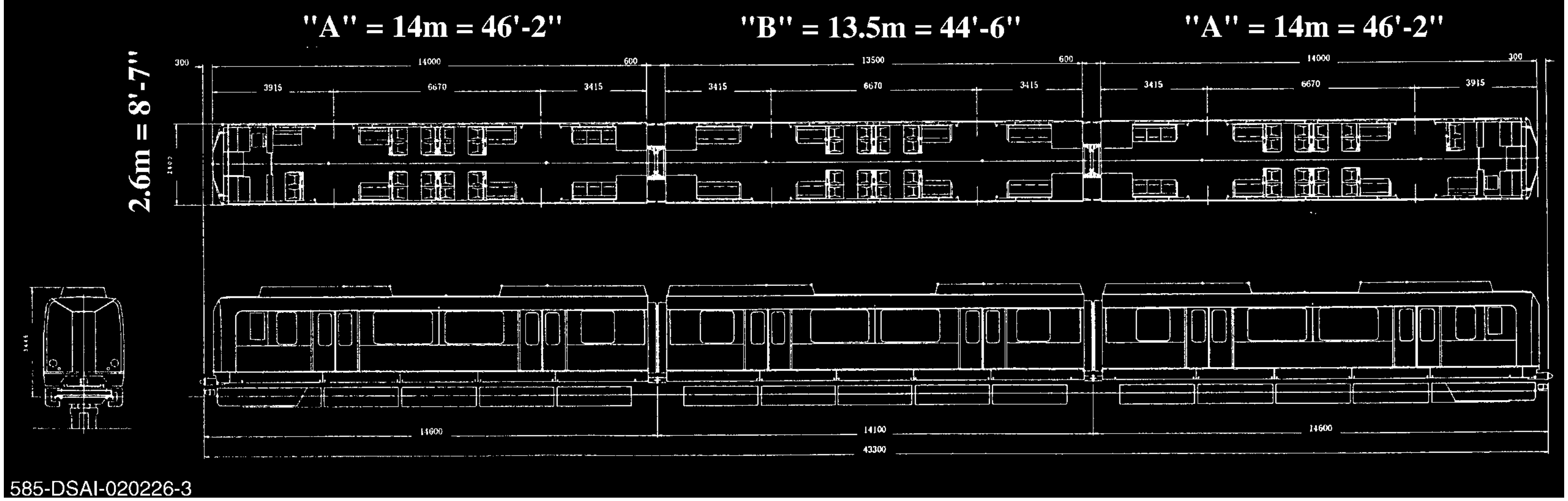


Figure 4-1. Proposed Tobukyu 3-Car Train Layout

vehicle body structural components to withstand peak quasi-static loads expected in service life. The fatigue life of the vehicle body and components is also important but the MUSA reports do not address this. It is important to know the basis of the 20 year life for the vehicle. Although the manufacturer is very experienced, a design rationale for the life span should be provided.

The expected 20 year life span for the vehicle probably results from the combined effects of fatigue and corrosion. The honeycomb structure can be vulnerable to corrosion due to trapped water, humidity, and galvanic action with other materials at connections. The fatigue life depends on:

- Speed and guideway irregularities/dynamic amplitude
- Vehicle miles/number of cycles.

The stated 20 years life is short of the 30 year FTA requirement for the Maglev vehicles, which by virtue of their contact-free operations on the guideway, are expected to be "maintenance free" and provide long service life, to justify the high initial cost. In fact, the Aichi Prefecture report [1], stated that the time in which the HSST system will be profitable is somewhat longer than for the monorail system.

4.3 Operational Experiences

The different HSST developmental vehicles have carried a sizable number of passengers since 1974 at different exposition and test locations as indicated in Figure 2-4. The sum total of passengers at all expositions exceeds 3 million. The test sites report a similar number. The 100-S at Nagoya had carried 13,837 passengers over a distance of 62,370 km prior to December 31, 2001. The 100-L at Nagoya carried 25,991 passengers over a distance of 130,206 km during the same time period.

Consider a 15 km long route which is expected to carry 12,000 passengers in each direction per hour (FTA requirement). Assume that the service runs for 20 hours in a 24 hour day, also an FTA requirement. The total number of passenger km in 20 years is:

$$15 \times 2 \times 12000 \times 20 \times 365 \times 20 = 42 \times 10^9$$

The total passenger km for the 100-S is 0.88×10^9. For the 100-L, the passenger km is 1.62×10^9. The operational experience to date is therefore a small portion (< 4%) of the expected service life of the system.

In MUSA Report #3 [4], the component failures during an endurance test lasting for 3 years and 2 months are presented. There are failures such as hydraulic fluid losses, etc. But a major failure was the de-levitation of modules because of unstable levitation control. The failure rate is noticeable—three times in three years, with a total running distance of 41,259 km. This was attributed to weakness in the rail structure. It is important to note that over a 20 year period, a vehicle is typically expected to traverse about 500 x10^4 km, which is more than 100 times the distance simulated in the endurance test.

4.4 Train Capacity

Capacity refers here to the maximum passenger-carrying capacity of any transit-type system. This results from a simple multiplication of the passenger capacity of each train/consist and the number of trains/consists per hour in each direction.

The critical factors in determining the capacity are:

- The capacity of each car, including seated and standee passengers, and the ability of the car to provide sufficient floor space, weight-carrying ability, and storage area.

- The length of the trains formed by these cars, which in turn requires stations of adequate length, and layouts to permit good passenger flow on and off the trains. The ability to load and unload passengers in a short, set stop time is vital if schedules are to be maintained.

- The design of the train control system, signal and communications, train protection, level of safety, system redundancy and margin for malfunctions all influence the safe train headway, or spacing in time. The ability to run trains continuously at short headways, allowing for discrepancies in the transportation network, is a challenging task requiring a high level of sophistication in the system and dedication on the part of the management, operating and maintenance staffs.

- The performance of the trains (acceleration, deceleration and maximum speed) interact with the operating schedule and the train control system to limit reductions in safe headway. In extreme cases with short lengths between stops, the physical train length is a factor. Also, given maximum acceleration/deceleration rates suitable for standees (0.15 g fore-aft as an example), shorter station spacing may not permit maximum speeds to ever be attained over a significant portion of the journey.

4.4.1 CHSST System Parameters.

The Tobukyu Expo line capacity is planned for 4000 passengers/hour in each direction, claiming 400-passenger trains at 6-min headways operated automatically under ATO. The CHSST descriptive material refers to the 400-passengers capacity of these 3-car consists. However, this assumes tightly packed 3-car consists (A-B-A) of “long” cars similar to the 100-L, with only 0.14 m^2 (1.5 sq. ft) of floor area allowed per standee. Using a more suitable 0.3 m^2/standee (3.3 sq. ft), the norm in the US and Europe, that train would have 242 passengers, according to data furnished by CHSST. It would require proportional adjustments in headway and/or number of cars in the consist to achieve 4000 passengers/hour/way, such as that 3-car train at 3m 38s headway. The 1993 Aichi Prefecture Report [1] assumed “short” 100-S cars, which with the 0.3 m^2/standee criterion resulted in a 4-car (ABBA), 200-passenger consist. (A 5-car ABBBA consist of 100-S cars with 250 passengers would be roughly the same 42 m length as a 3-car ABA consist of 100-L cars with 242 passengers.) Note that the CHSST cars are somewhat narrower at 2.6 m than standard rail cars at 3 m.

4.4.2 Capacity Example for Urban System

Table 4-2 shows the system capacity as a function of trains/hour (also expressed as headway) and train size (passengers/train) for a 242-passenger and 400-passenger train. To meet the FTA 12,000 passengers/hour/way requirement, 8-car trains (400 passengers) with 100-S cars would have to operate continuously at 2-min headways, or 12-car trains (600 passengers) at 3-min headways, etc. (The 100-S cars are used since these are the only CHSST design that has curving capability down to 25 m, still shy of the present FTA min requirement of 18.3 m/60 ft).

Table 4-2. System Passenger Capacity vs. Train Headway and No. of Passengers/Train

Trains Per Hour	Passengers per Train	System Capacity**	Passengers per Train	System Capacity**
*10 (@ 6 min.)	242	2420	400	4000
12 (@ 5 min.)	242	2904	400	4800
15 (@ 4 min.)	242	3630	400	6000
20 (@ 3 min.)	242	4840	400	8000
30 (@ 2 min.)	242	7260	400	12,000

*Present CHSST Plan **Passengers/Hr, Each Way

Achieving this would be interdependent with the quality and design of the train control system, train performance, equipment and human reliability levels, level of safety, control of maintenance practices, station lengths, station stop, passenger load and unload times, etc. The 8-car train would be 66 m/218 ft long and the 12-car train 50% longer than that at nearly 100 m/325 ft.. These combinations of long trains and short headways combine to demonstrate how large the 12,000 passengers/hour goal is, especially in view of day-to-day operations.

4.4.3 Effect of Maximum Speed on Trip Time

For urban maglev, the FTA specified performance capability of 160 kph (44.4 m/s) with corresponding acceleration and deceleration performance capabilities of 0.16 g are important criteria for trip time assessment. For station spacing of only 1-2 km or less, it is recognized that acceleration and deceleration performance, more so than maximum speed capability, are the important considerations for determining trip time. However, for station spacings on the order of 5-10 km or more, typified by corridor service between major activity centers, for example a city center to an airport, minimizing trip time requires that an urban maglev system should have the FTA desired speed performance capability of the 160 kph

Per the MUSA reports reviewed, the presently designed Chubu HSST 100L and 100S vehicles have maximum specified speeds of 100-110 kph with acceleration/deceleration capabilities of about 0.11g. Chubu did state that the propulsion systems for both vehicles do have the capability of operating up to 130 kph. As stated by Chubu, they also have the capability to operate at higher accelerations than they have specified with the provision that maximum power performance called for must be limited to the capability of the present design. This means that the transition from constant thrust to variable thrust must occur at lower speeds when accelerating at higher than the specified acceleration performance.

Short Station Spacing

The trip time was evaluated in light of the present CHSST permitted speed of 100 kph, with the higher speed of 130 kph being a likely possible increase with minimum consequences for the present vehicle and guideway design. Also, the FTA requirement of 160 kph (100 mph) capability was included in this assessment. Figure 4-2 shows that a 1.1 km (0.7 mi.) leg would be needed to touch 130 kph and a 1.7 km (1.1 mi.) leg needed to touch 160 kph. This is using the maximum FTA required acceleration/deceleration rate of 1.6 m/sec^2 (0.16 g, appropriate max for standees) plus allowable jerk of .05 g/sec. In each case, zero time at the peak speed was accumulated. A reasonable safe braking margin of _ the actual braking distance was added for each of these legs.

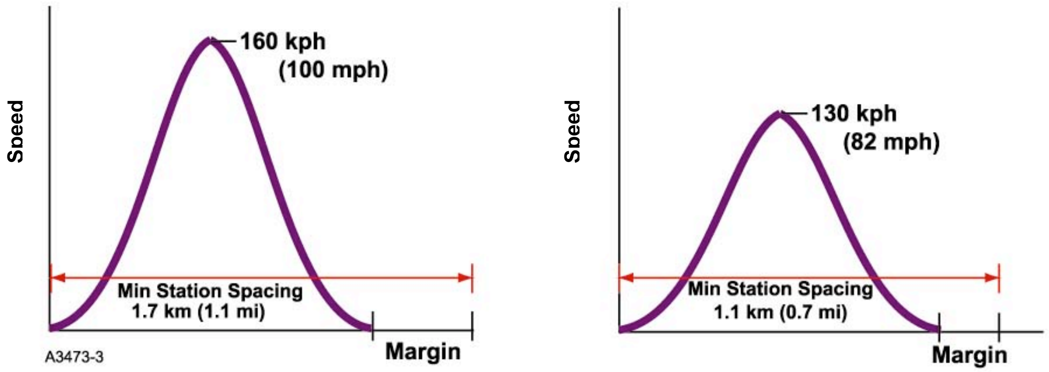


Figure 4-2. Station-to-Station Distances Needed to Utilize Higher Top Speeds

For the potential benefit of higher speeds on trip times, we also evaluated time savings on a relatively longer leg of 2 km, typifying the general range of such longer legs in the urban-suburban network (Figure 4-3). The effects of a speed increase from 100 kph to 130 kph produced a trip time reduction of 10 sec (from 1m 30s to 1m 20s) and an additional speed increase to 160 kph gave an additional reduction of 5 sec to 1m 15s. The latter had only a 15 sec period at 160 kph (20% of the leg time).

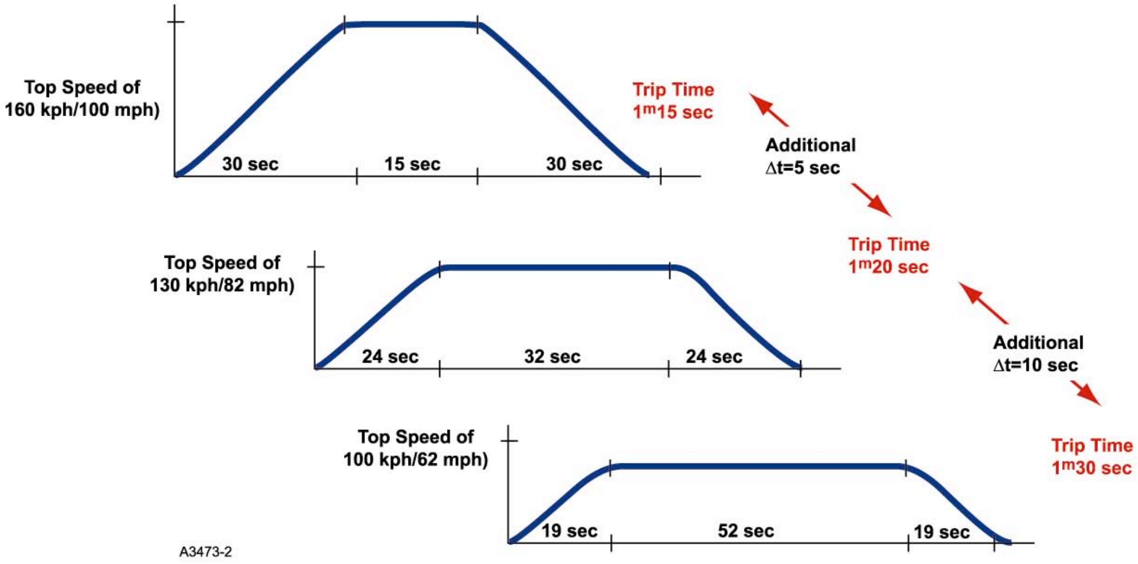


Figure 4-3. Trip Time for 2 km Station Spacing

These evaluations show how diminishing returns are produced from higher speeds for the short station spacing scenario. Therefore, the speed increase from 100 to 130 kph, if achievable by CHSST without significant design changes, may be acceptable as a first step for its application in the U.S. on routes with short station spacing.

Long Station Spacing

A trip time comparative assessment was performed for a 10-km station spacing using the FTA desired performance as a baseline. As shown in Figure 4-3, the trip time using FTA requirements and idealized acceleration-deceleration profiles would be approximately 4.2 minutes (252 seconds). Using the Chubu currently specified 100 km/h and 0.11g performance level for the 100L vehicle the CHSST would have a trip time of more than 6.4 minutes (385 seconds) or a trip requirement of more than 50% for the route scenario considered here. This difference would be reduced to about a 25% difference (320 second trip time) for the case of upgrading the 100L vehicle's performance to the 130 km/h speed capability.

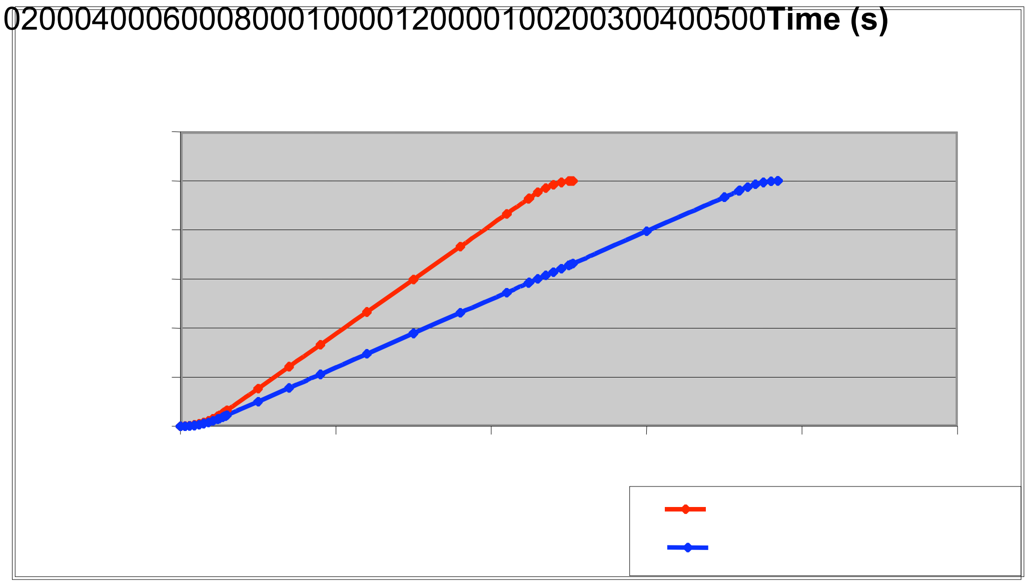


Figure 4-4. Trip Time for 10 km Station Spacing

Whether even a 25% trip time difference would be acceptable to a potential urban maglev system operator would of course be dependant upon the desired operating service goals of that operator. For station spacing significantly larger than 10 km, it would appear that having 160-km/h operational capabilities would be mandatory.

4.4.4 Impact on Station Size

The FTA specification for station size includes a typical footprint of 40m long assuming a 4-car train and 2 tracks/3 platforms, although this depends on train size. It is clear from the discussion in paragraph 4.4.2 above that a station with a 40m platform could not accommodate trains of sufficient length to meet the capacity requirement of 12,000 passengers/hour/direction. The example 8-car consist of 100-S cars with 400 passengers would have to operate at 2-min headways (30 trains/hour), and the platform would be 70m (approaching 250 ft, without additional stopping tolerance). Even considering the smaller width of the CHSST cars at 8.5 ft vs. standard cars at nearly 10 ft, the platform sizes for such system capacities would have to be much larger than the FTA guideline. The 40m platform would be more consistent with trains operating at a 1-min or less headway.

4.4.5 Summary of Capacity Issues for CHSST

- A projected speed increase from 110 kph to 130 kph, with potentially low design impact, can accomplish many of the time reductions for typical likely urban-suburban system networks. The CHSST vehicle potential to serve as a Maglev for U.S. urban areas may be evaluated in that light.

- The FTA required acceleration/deceleration rate of 1.6 m/sec^2 (0.16 g) plus allowable jerk of .05 g/sec is stated to be achievable with the CHSST design (and is the maximum appropriate for standees) and relates to the speed issue above.

- System capacity with CHSST cars for the FTA passenger density requires very short headways (down in the 2 minute range) with long trains over 200 ft. Reductions in capacity produce direct proportional reductions in train size and/or train frequency.

4.5 Curving Capability

Curving is limited by clearances in the mechanical brakes and skids, since mechanical braking uses a floating caliper on the outer flange of the main steel levitation/guidance/ LIM rail section.

During vertical curve negotiation, a 1500 m radius limit would normally apply to the longer 100-L cars, and 1000 m radius to the shorter 100-S car. The longer car is operated on the test track to 1000 m radius but without the extra tolerance margins expected for a revenue line. For example, these limits are based on allowing for an air spring failure, therefore reducing bogie compliance to the curve.

On lateral curves for the Tobukyu line, minimum radius is 75 m to be taken at 30 kph using a 5° cant and lateral (relative to the car) load felt of .075 g at passenger level. On the test track, the 100 m minimum radius turn with 8° cant is safely negotiated at 42-44 kph. In all cases, these are above balance speed, with the lateral in-car g-load for comfort prevailing.

The HSST 100-S car can negotiate a 25m curve. The minimum radius that can be negotiated by the 100-L car is 50m. Clearly, the present FTA requirement that a minimum curve radius of 18.3m be negotiated is not satisfied by the HSST. If MUSA is proposing 100-L cars for U.S. applications, they must also identify in how many potential routes these cars can be used with their 50 m turn radius. Based on the percentage of applicable routes, these may be justified to provide Urban Maglev transportation.

4.6 Passenger Egress and Safety

There are two doors on each side of the car, similar to standard U.S. transit car practice. These can be either single or double-sliding doors with the usual interlocks: shut before motion starts, detect/retract if obstructed, etc. In the present and planned cars, there are no apparent additional emergency egress measures, such as fully opening removable windows or roof hatches. The car-to-car end doors would be difficult to use for train egress, as for any coupled transit car with end vestibules and exit doors.

Egress in the event of fire and smoke is an essential requirement. The passengers need to be able to open the doors, using an alarm in the car, during an emergency. The doors should open after the vehicle comes to a complete halt. The passengers must be able to step on the guideway and walk on it towards the station, or get down to ground level by some means. Walkways were mentioned as being required on the Tobukyu line. This issue must be addressed in detail by MUSA.

4.7 Vehicle Crashworthiness

The vehicle body does not have any specific crashworthy features to absorb energy in the event of a collision with another car or a large object on the guideway (such as a fallen tree or large stone/obstruction placed by vandals). The designers of HSST intentionally did not include this feature, since such collision possibilities are apparently eliminated in their signal systems and safety inspection procedures.

For Maglev vehicles in the U.S., crashworthiness at full operating speeds may not be required. However, during maintenance and yard operations, and at the stations, a crashworthiness requirement at some slow speed (say in the 15-30 kph range) is desirable. Without increasing the vehicle weight significantly, MUSA and CHSST should satisfy this requirement by redesign of the end sections of the vehicles.

4.8 Dynamics and Ride Quality

Generally, to assess the dynamics and ride quality in any guided transport vehicle, a rigorous dynamic model is used, followed by full scale testing with an instrumented car. Apparently, the HSST vehicles have undergone rigorous test procedures to improve their design. In the early stages (1991), the vehicle suffered large yaw excursions, a common problem with Maglev vehicles lacking adequate lateral damping and guidance control.

Matsumoto and co-workers [6] performed tests on the Nagoya track and their results showed significant improvement with the use of yaw dampers. The yaw oscillations no longer exceeded those of some of the conventional vehicles. Additional test data on ride quality in terms of g levels has shown the level to be within the allowable limit for vehicle speeds up to 100 kph.

The various operational and limit guideway tolerances must be considered in assessing the ride quality and the vehicle dynamic behavior. The CHSST guideway tolerance plan was shown in Section 3. The limiting factor for the guideway tolerance appears to be the vehicle dynamic behavior, i.e. large excursions with interference between components such as the brake calipers and other module components, rather than the ride quality for the passenger.

If the CHSST needs to run with a maximum speed of 130 kph in the U.S., the guideway tolerances may have to be made less stringent and/or the vehicle components must be redesigned to reduce the interference. For that purpose, a rigorous dynamic model accounting for guidance and levitation forces/displacements, inertial properties of vehicle components and bending flexibility of the car body and floor, is required. These models, generally available in the literature, should be exercised for the purpose of evaluating the vehicle behavior and ride quality at 130 kph. Alternately, tests should be run at 130 kph on instrumented vehicles, thereby developing a redesign via trial and error.

4.9 Vehicle Manufacturing

The CHSST vehicle manufacturing core group and the major subcontractors are well known and have proven experience. Nippon Sharyo is responsible for the car body and assembly. Although this company has had extensive experience in car building, when it came time to build the HSST-100 car bodies, the chief engineer of the company expressed significant concerns about this project to the FTA and MUSA team visiting them in Japan. These include:

- Little margin in manufacturing cost, especially for low vehicle quantity

- Challenging weight requirements—vendors are not typically experienced in manufacturing the vehicle and parts. They cannot adopt special or untried techniques to optimize the weight. This is an important aspect, as the Maglev vehicle weight is critical to its levitation and propulsion performance, which are discussed in later sections.
- The required coordination between the subcontractors is complex.

The problem of manufacturing HSST vehicles for U.S. applications could be even greater because of the U.S. mandatory requirements plus the FTA system requirements. Also, the manufacturing infrastructure in the U.S. for rail type vehicles is not as strong as in Japan. MUSA must identify companies or subcontractors in the U.S. who can build part of the HSST vehicle or support Japanese manufacturers to satisfy the “Buy America” provision.

4.10 U.S. Mandatory and FTA System Requirements

4.10.1 U.S. Mandatory Requirements

- **ADA:**
  The system should be usable by all, including the blind and those dependent on a wheel chair. Because of the smaller width of Maglev vehicles compared to conventional vehicles, problems may arise in accommodating this requirement. Suitable interior car seating arrangements need to be developed.

- **Fire and Smoke Safety:**
  U.S. flammability and smoke emission requirements as applied to passenger, vehicles and interiors, etc., and NEPA 130 requirements for detection and suppression of fire exist. These shall be satisfied in the interior design of the vehicle structure.

- **Egress:**
  The FRA requirements for access and egress are presented in 49CFR, part 223.25. It requires that each passenger car have at least four deployable emergency windows. At present the HSST vehicles use doors for entry, exit and egress. Further studies are required to evaluate whether or not the door egress alone is adequate especially when the vehicle is occupied to its full capacity.

- **Crashworthiness:**
  The vehicles are to be designed for crashworthiness to protect passengers in the event of the Maglev vehicle hitting a large obstruction such as fallen tree branches, maintenance equipment, or objects placed by vandals,. The present vehicles' ability to withstand even low speed impacts is unknown. MUSA must evaluate the level of crashworthiness that now exists in terms of speed vs. size and weight of obstruction.

4.10.2 The FTA System Requirements

- **Curve Negotiation:**
  The vehicle should be capable of negotiating lateral curves of 18.3 m radius and vertical curves of 1000 m. The 100-L car is designed to negotiate 50m or higher radius horizontal curves and 1500 m or higher radius vertical curves. The 100-S car can negotiate 25 m or higher radius horizontal curves and 1000 m or higher radius vertical curves. MUSA should evaluate opportunities (Maglev locations) in the U.S. where 100-L cars can be used.

- **Maximum Speed:**
  The FTA requirement is 160 kph peak speed and an average speed of 50 kph. The HSST vehicles are expected to operate at 100 kph peak speed in Japan. Apparently they can be used to run at 130 kph without major design changes. This speed level may be acceptable on some route scenarios without sacrificing the trip times achievable at 160 kph. The effect of this higher speed on ride comfort and safety needs to be assessed. This is discussed further in Chapter 6 on Propulsion Systems and Power.

- **Vehicle Life:**
  The U.S. Maglev vehicle is expected to provide a service life of 30 years according to the FTA requirement. According to the MUSA report, the service life of the vehicles is 20 years. The method of determination of a 20 year life span, which is a combination of fatigue, corrosion and wear, is not given in the MUSA reports. MUSA must present analysis or historical data on this, and explore methods of increasing the life to 30 years.

- **Ride Quality:**
  The FTA ride quality requirement of "1 hour comfort level" is based on ISO 2631/1, 1985. This standard has been adopted by the HSST developers. The test data shown to the authors for the current design and the allowable guideway tolerances, up to a speed of 100 kph, seem to meet the FTA requirements. MUSA and CHSST should use a general purpose non-linear dynamic model to evaluate the ride quality and

vehicle dynamic behavior at higher speeds, guideway tolerance, and service limits, plus consider any design modifications which are introduced.

4.11 Vehicle Issues and Evaluation

- The CHSST system uses a reasonably mature Maglev vehicle capable of transporting passengers in urban areas. However, the vehicle falls short of satisfying certain U.S. mandatory and FTA system requirements identified in the previous section. If the CHSST cars can be operated safely at 130 kph without major redesign of the vehicle, it may be considered for U.S. application in certain site-specific scenarios, providing other issues (discussed in other chapters) are resolved at this speed.

- Despite two decades of development the CHSST operational experience in terms of passenger km is a small fraction of the expected usage during the life of the system. CHSST has made significant efforts in developing the technology during these decades, and performed a number of safety and performance evaluation tests However, the vehicle endurance testing was conducted over only a small percentage of the vehicle miles expected from the FTA requirements.

- To improve the performance of the vehicle, a critical consideration is reducing the weight of the vehicle structure. The aluminum construction does save weight compared to steel. However, it is not clear how the weight is optimized. Modern methods of using combinations of carbon composites and cheaper fiberglass may be a solution to be considered for the U.S. applications. Vehicle manufacturing, even with the present aluminum design, can pose problems due to the lack of appropriate infrastructure, particularly for vendors who prefer the off the shelf or previously made components that can potentially increase the weight of the vehicle structure. At the same time, crashworthiness and energy absorption need to be considered.

5 Levitation and Guidance

5.1 System Features

The HSST levitation system is based on a normal electromagnetic suspension (EMS) with active vertical and passive lateral control, and having the levitation modules integrated with a short-stator linear induction motor (LIM) [2]. The steel guideway used for levitation is also used as "backiron" for a single-sided LIM in which an aluminum reaction plate is mounted to the steel.

The technology is based on an earlier generation Transrapid version, the TR04, and the original technology was purchased from Transrapid in 1974 by Japan Air Lines.

A U-shaped levitation magnet using an iron core and copper windings is attracted to a U-shaped rail; this arrangement generates both levitation and lateral centering forces. A simplified version of this suspension is shown in Figure 5-1, which defines the magnetic operating gap, □.

Each levitation module has an inductive sensor that measures the magnetic operating air gap. Vertical control is accomplished actively; this is necessary in order to stabilize the vertical suspension which is unstable without feedback. Lateral control is done passively with some damping provided by airbags in the mechanical secondary suspension.

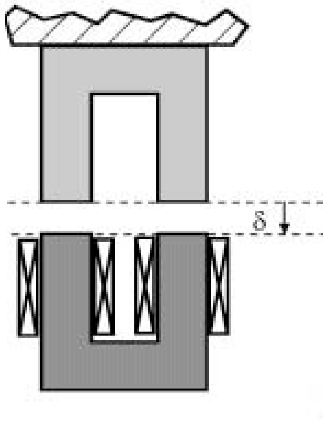


Figure 5-1. Simplified EMS Suspension with U-shaped Guideway [8]

Details of the levitation and guidance force profiles as a function of vertical airgap and lateral position, taken from a similar system [8] are shown in Figure 5-2. Note that a change in the lateral position (x) affects both the lateral restoring force (f_{guid}) and the levitation force (f_{lev}). The suspension can accommodate lateral forces of approximately 0.3 g. Although there is vertical control, apparently there is no lateral control, which makes the lateral suspension under-damped.

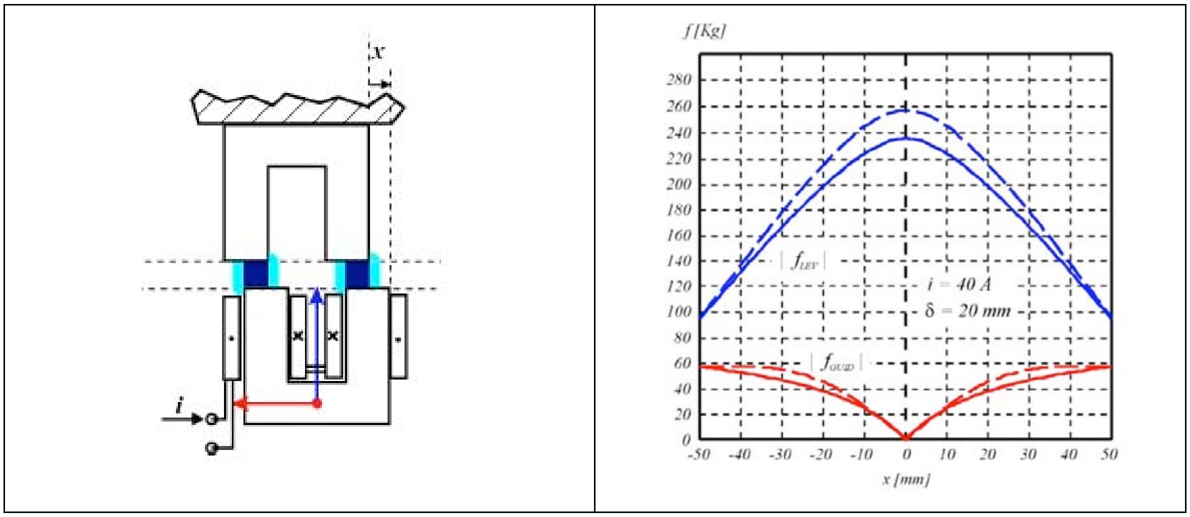


Figure 5-2. Detail of Levitation and Guidance Forces with Lateral Deflection

5.2 Design Basis and Specifications

Selected levitation system specifications of HSST are shown in Table 5-1. Of note is the airgap; the magnetic airgap is nominally 8 millimeters, while the effective mechanical airgap is only 6 millimeters due to coatings on the steel and other mechanical interferences that use 2 millimeters. Also, note that levitation power increases as speed increases; this is due to additional control power needed at higher speed.

Table 5-1. Levitation System Selected Specifications

Nominal levitation airgap (magnetic)	8 mm
Nominal levitation airgap (mechanical)	6 mm
Levitation power (0 kph)	700 Watts/tonne
Levitation power (100 kph)	900 Watts/tonne
Levitation module power supply	275 VDC
Levitation backup power	Provided by batteries; approximately 30 second capacity
Magnet driver	2-quadrant chopper operating at 4 kHz
Gap sensor	Inductive proximity sensor
Control method	Digital signal processor
Control algorithm	PDI (Proportional, derivative, integral) control

5.2.1 Vertical control

For electromagnetic suspensions, active control is mandatory as the attractive force is inversely proportional to airgap, and so is unstable without feedback. HSST utilizes an inductive proximity sensor that measures the distance between the magnet coil and the rail. Using the signal from the proximity sensor, HSST employs PDI (proportional, derivative, integral) control in order to stabilize the suspension vertically. Control is implemented with a digital signal processor and magnet control power is provided by a 2-quadrant chopper operating at 4 kHz from a 275 Volt DC bus.

Without active control, or if there is an airgap sensor failure, such an EMS suspension is unstable. The magnet will either clamp to the rail, or fall off completely; therefore, this can be an intolerable failure mode. According to HSST, there is a possible single point failure mode in the suspension and control. As is noted in MUSA [4], there have been several instances of levitation modules de-levitating due to sensor failures and the like. The details of this failure mode have not yet been forthcoming from HSST, which is studying this issue.

5.2.2 Lateral control

In HSST, there is no active lateral control. The suspension is stable, but under-damped laterally. Some damping is provided laterally by airbags on the secondary side (module to car body), but HSST does not have data and analysis describing the damping ratio. During technical meetings in Nagoya, Mr. Yoshihide Yasuda from HSST did explain that HSST has done some computer modeling, which shows a lateral offset of 6 millimeters when going through a 100-meter radius curve, which is below the 15-millimeter allowable deflection. However, there has been no analysis forthcoming yet from HSST describing the system behavior under wind gusts, passing trains, etc. Lateral guidance is important since a likely US Urban Maglev alignment would include two-way operation with passing trains. HSST should do further work on the dynamics of the lateral suspension as well.

5.2.3 Backup power

Backup power for the levitation modules is provided by a bank of rechargeable batteries. The battery bank is able to provide levitation power for approximately 30 seconds. This should be sufficient for a safe landing should levitation main power be lost. However, the backup battery capacity should be further evaluated to determine whether there is sufficient energy capacity to the LIM for safe braking during a power outage.

5.3 Levitation Characteristics

5.3.1 Levitation power vs. speed

HSST has test data in the 0 – 100 kph range showing levitation power. As speed increases, levitation power increases due to higher control power requirements to overcome guideway irregularities. Figure 5-3 shows the predicted levitation power over the speed range 100 – 160 kph. If the suspension is to be operated at the higher speeds (over 100 kph), the power-handling capability of the suspension coils needs to be further evaluated.

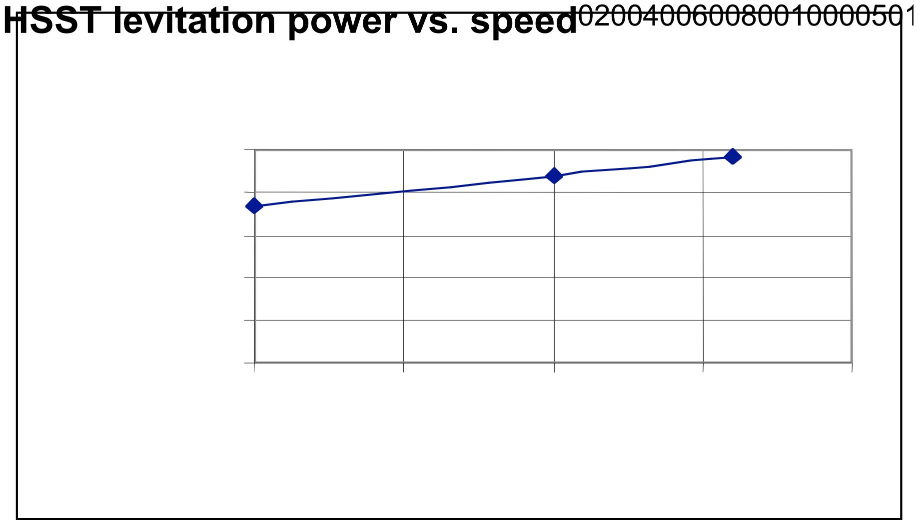


Figure 5-3. Levitation Power vs. Speed (Extrapolated Above 100 kph)

5.3.2 Levitation power vs. Airgap

There is a strong relationship between the operating airgap and power dissipation in an electromagnetic suspension, and there is a strong power penalty incurred when operating at a larger airgap. The functional dependence can be inferred by considering the simplified (2D) model in Figure 5-1. The effective magnetic operating airgap is δ, the pole area is A and there are N turns energized with DC current I.

The airgap magnetic flux density assuming no saturation in the steel, and a purely 2-dimensional suspension is:

$$B_g = \frac{\mu_o NI}{2\delta} \qquad (5\text{-}1)$$

The lift force is given by:

$$F_L = Mg = \frac{B_g^2 A}{\square_o} = \frac{\square_o (NI)^2 A}{4\square^2} \tag{5-2}$$

The power dissipation in the winding is:

$$P_{coil} = I^2 R \tag{5-3}$$

where *R* is the winding resistance. Combining (5-1), (5-2) and (5-3) results in a relationship between operating airgap, total lifted weight, and power dissipation, which is:

$$P_{coil} = \frac{(4R)}{(\square_o N^2 A)}(Mg)\square^2 \tag{5-4}$$

The first term is a constant, which includes the effects of winding resistance. Note that winding resistance increases with temperature. The second term is the weight of the train, and the third term is the operating airgap. This scaling law favors lighter vehicles operating at a small airgap. From this, we can determine a power dissipation if the operating airgap deviates from a nominal value of 8 millimeters (Figure 5-4). For instance, increasing the airgap from 8 to 10 millimeters requires a 56% increase in suspension power dissipation. Doubling the airgap increases the suspension power dissipation by a factor of four.

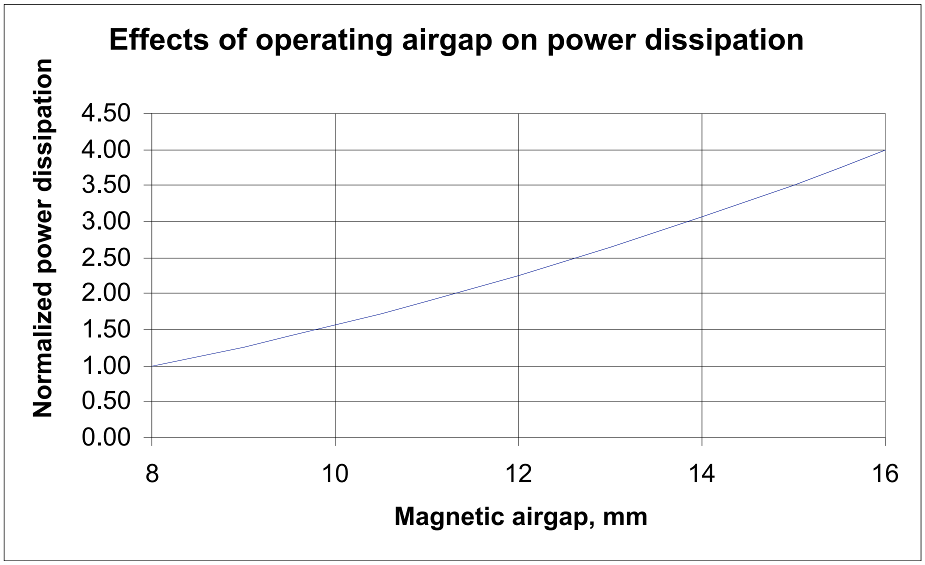


Figure 5-4. Effects of Operating Airgap on Power Dissipation

5.4 U.S. Mandatory and FTA System Requirements

Currently there is no FTA requirement on the minimum allowable limitation gap for the Maglev vehicles. The small gap in the EMS and its potential impact on safety and smooth vehicle movement has been a general concern.

Also, the control system should be further evaluated. There is anecdotal evidence from HSST that there are possible single-point failure modes in the levitation and control; without active feedback, EMS suspensions are unstable so the control system should have redundancy.

MUSA Report 3 [4] indicates that there were three de-levitation incidents in the vehicle endurance tests performed over a period of about 3 years over a distance of 41 km. This shows that the levitation system reliability may need to be further improved, even though the cause of the de-levitation was attributed to weak spots on the guideway.

5.5 Evaluation and Issues

5.5.1 Overall Impressions

The test program implemented by HSST with regard to the levitation modules has been lengthy and comprehensive, but empirical in nature. There has been little or no analytic information provided to the FTA team, and the test data provided has been summary in nature. There have been several instances of vehicle de-levitation during testing, and further demonstration is required to determine whether the vertical control system is sufficiently robust and redundant to meet U.S. safety standards. Other issues such as the lateral suspension need to be addressed, especially with regard to ride quality and the ability to withstand wind gusts and aerodynamic forces arising from passing trains.

The vehicle is heavy and this constrains significantly the designs of the levitation, guidance, propulsion and guideway modules. Any weight reduction achievable, e.g., the car body, will have a significant trickle-down effect on total vehicle weight and cost. As an example, a reduction in train weight results in a reduction in levitation module weight; a lighter levitation module requires less levitation force, etc. This should be thoroughly evaluated before adoption in the U.S.

5.5.2 Overall advantages of EMS

A significant advantage of the HSST EMS levitation is that there is lift at zero speed. Therefore, landing wheels are not needed as are needed in electrodynamic (EDS) Maglev. For the urban environment where there are frequent starts and stops there is another significant advantage to EMS since there is no magnetic “drag peak” to transition as in EDS. In EDS the drag peak must be overcome by the linear motor, whereas the EMS levitation is free of this restriction.

5.5.3 Vertical Control System

HSST has indicated that there is a possible single-point failure mode in the levitation system, as described previously. This must be evaluated with regard to the FTA overall safety requirements. The reliability of the levitation control system may need to be further improved.

5.5.4 Small Levitation Gap of EMS

The magnetic levitation airgap (from steel to steel) is nominally 8 millimeters. However, other interferences reduce the effective mechanical airgap to 6 millimeters, nominal. During testing, reported results [7] show maximum peak-to-peak levitation gap deflections of ±3 millimeters at 100 kilometers per hour. The trend in the test data was for higher peak-to-peak deflections at higher speeds; hence it is expected that the peak-peak deflection will be even higher at the FTA requirement top speed of 160 kilometers per hour. Therefore, peak-to-peak deflections in the levitation module are a significant fraction of the 6-millimeter nominal mechanical airgap. This needs to be further evaluated, especially in light of allowable guideway irregularity tolerances.

With a copper-wound EMS magnet, there is a severe power penalty in increasing the operating airgap. It would be desirable to increase the gap and improve its control by use of permanent magnets to assist levitation and advanced digital control techniques, but this requires redesign of the system.

The small levitation airgap may also be a factor on the stringent guideway construction tolerances, which can increase construction and maintenance costs [9].

5.5.5 Lateral Guidance

Lateral guidance is accomplished passively; there is no active control of lateral position. Reported results [7] show significant lateral oscillations during normal operation. It is unclear from the available literature what the lateral load capacity of the system is before hitting the guidance skid. HSST has apparently not performed tests to determine lateral deflections under wind gusts from passing trains, nor the aerodynamic effects due to the trains' passing in opposing directions.

5.5.6 Motor-levitation Module Geometry Interactions

There is another interaction that constrains the design of the levitation section and the linear induction motor. The linear motor and levitation sections are stacked, in that variation in the airgap of one inversely affects the airgap of the other. Some improvement in LIM performance can be achieved by operating at a smaller airgap; however the LIM/levitation stack-up constrains this modification. Another factor in the LIM/levitation module interaction is that the LIM attractive force opposes the levitation module attractive force, and hence the levitation module must produce more lift than the weight of the train. It is unknown whether HSST has evaluated the tradeoffs inherent in this LIM/levitation stack-up.

5.5.7 Maximum Speed

The maximum operating speed of HSST-100 is 100 kilometers per hour. For higher speeds, performance of the levitation module needs to be evaluated, with regard to

- Peak-to-peak deflections
- Lateral deflections
- Levitation power requirement.

Test data [7] show that the levitation power consumption increases approximately linearly with train speed; levitation power at 100 kph is approximately 880 Watts/tonne; extrapolating to 160 kph shows that the module will dissipate approximately 1000 Watts/tonne. This needs to be further evaluated to determine whether there is sufficient cooling.

6 Propulsion System And Power

6.1 Operational Experience

The CHSST development history dates from 1972 when, during its early phases, development was concentrated on a high-speed subscale model. From the late 1970s and onward, lower speed passenger carrying prototypes were built and demonstrated primarily at various exposition sites. With respect to the propulsion system all known HSST development and testing has been with the use of the linear induction motor (LIM).

Prior to the introduction of the 100-S version vehicle sometime in 1990, at least three versions of the HSST had been built and demonstrated on relatively short tracks where Chubu reported accumulated distances traveled of more than 40,000 km. With respect to the LIM, we were told that its development was based on the work of Prof. S. Nonaka. The FTA team has since identified several of his publications during that time period [10-15]. Upon review of those publications, we will report on the results of that research and development as it pertains to the design criteria for the CHSST LIM.

The 100-S version was extensively tested on the CHSST test track in Nagoya during the 1991-1992 period by the Japan Transportation Economics Research Center, Aichi Prefecture [1]. With respect to the propulsion system, the testing was all accomplished on the 100-S vehicle, as that was the only vehicle in existence during the test period. The 100-L vehicle was introduced in 1994 and supposedly takes advantage of the test experience gained on the 100-S vehicle.

6.2 Design Basis

6.2.1 System Level Requirements

Table 6-1 summarizes the CHSST principal top-level system requirements with respect to propulsion system design criteria as described in MUSA Report No.1 [3], and as supplemented by the information received during the FTA's team visit to Chubu.

Table 6-1. Selected Propulsion Related Operational Characteristics

Characteristic	**Specification 100-L**	**Specification 100-S**	**Potential Capability**
Maximum Operating Speed	27.8 m/s (100kph)	30.6 m/s (110kph)	36.1 m/s (130 kph)
Maximum Initial Acceleration	1.11 m/s^2 (4.0kph/s)	1.25 m/s^2 (4.5kph/s)	1.6 m/s^2 (5.8 kph/s)
Maximum Gradient	7%	7%	
Maximum Headwind	25 m/s	25 m/s	
Minimum Horizontal Curve Radius	50 m R	25 m R	
Minimum Vertical Curve Radius	1500 m R	1000 m R	

As shown in the above table, the maximum speed capability for the 100-L vehicle, as published in the MUSA report [2]is 100 kph. For the 100-S vehicle it is 110 kph as described in the Aichi Prefecture report. These speed capabilities were modified by CHSST during our visit where it was stated that each vehicle was designed to and could achieve a maximum speed of 130 kph. Acceleration performance capability was also upgraded during our visit to 1.5-1.6 m/s^2. However, the break point speed, the speed which transitions from the constant thrust regime to a speed-dependent one, would have to occur at a lower speed setting than is currently published.

6.2.2 Vehicle Requirements

Table 4-1 in Chapter 4 summarized the CHSST vehicle dimensions and weight. Table 6-2 reproduces the vehicle characteristics for convenience as they relate to propulsion system requirements.

Table 6-2. Selected Vehicle Characteristics

Characteristic	100-S Specification*	100-L Specification*
Vehicle Dimensions	8.5 m long 2.6 m wide 3.36 m high	14.0 m long 2.6 m wide 3.2 m high
Empty Weight	9 tonnes	17.5 tonnes
Maximum Loaded Weight	15 tonnes	28.0 tonnes
* “A” type or end/control vehicle		

The small differences in vehicle height between the 100-S and 100-L vehicles is probably more the result of the age differences between these two vehicles, and also that the 100-S was probably originally built as a test vehicle, whereas our understanding of the 100-L is that it is a passenger carrying prototype. For the analyses to follow it will be assumed that both versions will have the same height of 3.2 m. The maximum weights given in the table are most likely more related to levitation limits rather than to propulsion related issues.

6.2.3 Drag Resistance Requirements

Table 3-1 of the Aichi Prefecture report contains Chubu’s estimate of the drag characteristics for the HSST 100-S vehicle. The drag estimates were apparently based on the tests conducted on the 100-S vehicle, which are summarized in that section of the table. As shown, separate analytic models were empirically developed for each of the major drag components, namely magnetic, power collector, and aerodynamic drag. The modeling equations, on a per vehicle basis and when converted to metric SI units are as follow. In these equations W is the weight of the train in metric tonnes, V is the speed of the train in m/s, and N is the number of vehicles in the train.

Magnetic Drag. The magnetic drag force (in newtons) is given by two different relationships and depends on whether or not the train speed is greater than 5.6 m/s (20 kph) and is estimated as:

$D_m=3.354\cdot W\cdot V$ for $0\leq V<5.6$ m/s (6-1)
$D_m=(18.22+0.074\cdot V)W$ for $V\geq 5.6$ m/s (6-2)

Power Collector Drag. The power collector has been determined to have an approximate constant drag resistance value and is estimated as:

$$D_c=41.67 \text{ (newtons)} \qquad (6\text{-}3)$$

Aerodynamic Drag. The aerodynamic drag, which depends on both frontal area and train length, is estimated (for zero headwind) as:

$$D_a=(1.652+0.572\cdot N)V^2 \text{ (newtons)} \qquad (6\text{-}4)$$

Using the perhaps more familiar form for D_a as $D_a=0.5\rho AC_dV^2$ where A is the frontal cross sectional area of the vehicle and C_d is the composite aerodynamic drag coefficient including the effects for both frontal and total wetted area, one can then estimate C_d from the data given in Table 3-1. For a cross sectional area of the HSST 100 of about 8.6 m^2 and for an assumed value of the air density coefficient ρ of 1.225, we then get an estimated value of C_d as 0.443, which seems to be a reasonable coefficient based on the overall shape of the vehicle.

Composite Drag. From the above components we can then write for the case of zero gradient and zero headwind the composite drag as:

$$D=D_m+D_c+D_a \text{ (newtons)} \qquad (6\text{-}5)$$

Figure 6-1 provides the estimated drag resistance and mechanical output power for a two-vehicle 100-S train, and Figure 6-2 provides similar data for the two-vehicle 100-L train. Two-vehicle trains are considered here, since based on the equipment layout distribution descriptions provided to us the minimum sized consist appears to be a two-vehicle consist. Because of equipment layout the current 100-type versions are not intended to operate as single vehicles. As seen from the data, the magnetic drag is dominant for low speed operation and as to be expected the aerodynamic drag dominates at the higher speeds. These two drag resistance components also are roughly equivalent for speeds in the range of 10-13 m/s. At the 28m/s point (100 kph) the required mechanical output power is 71 kW and 78 kW respectively for the 100-S and 100-L 2-car trains.

Accounting for a positive gradient we would need to add to the composite drag D, the term $D_G=N(M\cdot g)\sin(\theta)$ where M is the mass of the vehicle in kg, g is the acceleration constant due to gravity, and $\theta=\tan^{-1}(G/100)$ where G is the gradient expressed as a percentage. Accounting for headwind, the D_a term would have to be modified accordingly by adding the headwind H in m/s to the vehicle velocity term, V. The impacts of these two effects will be discussed further on.

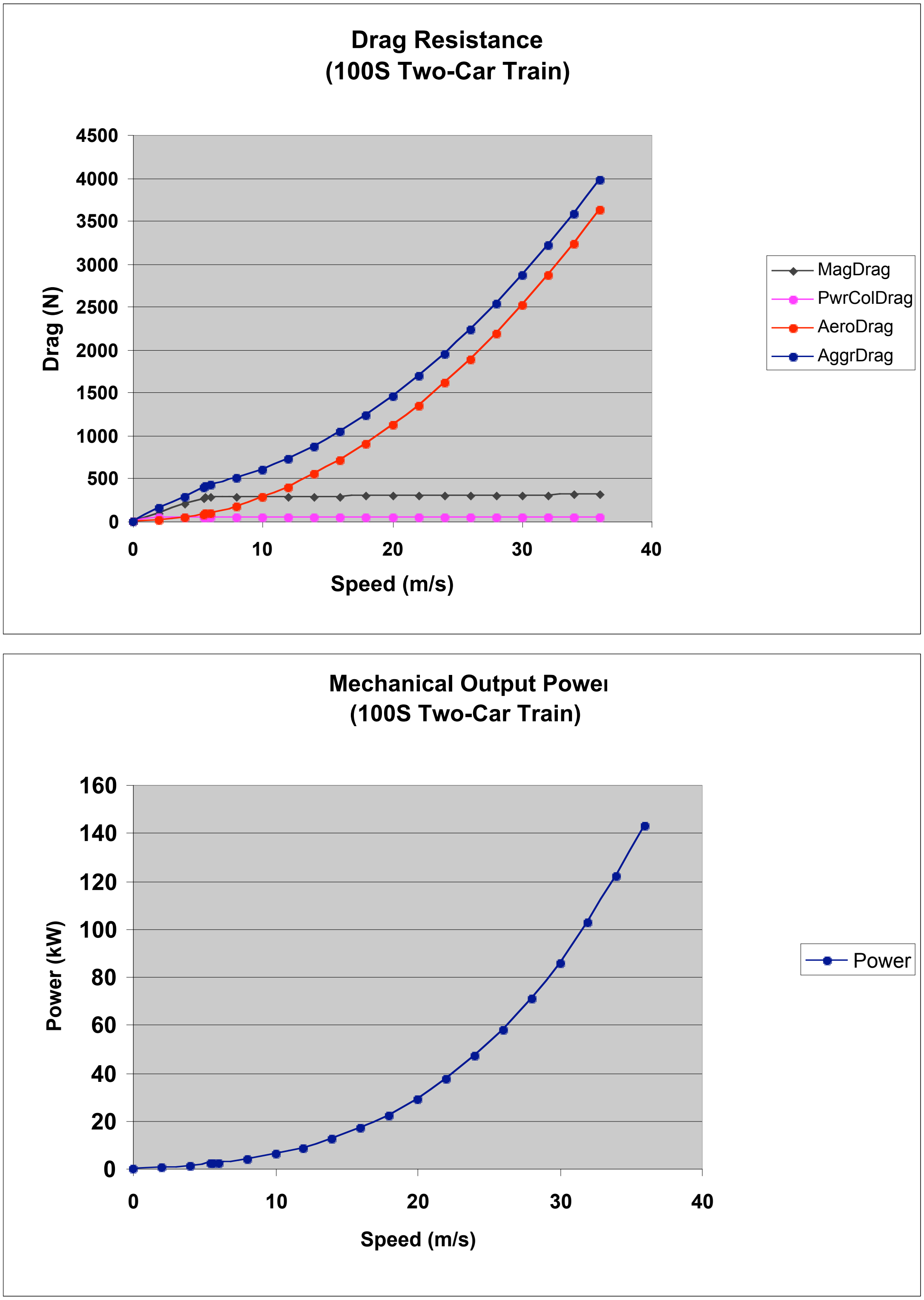


Figure 6-1. Drag and Power Characteristics of the CHSST 100-S

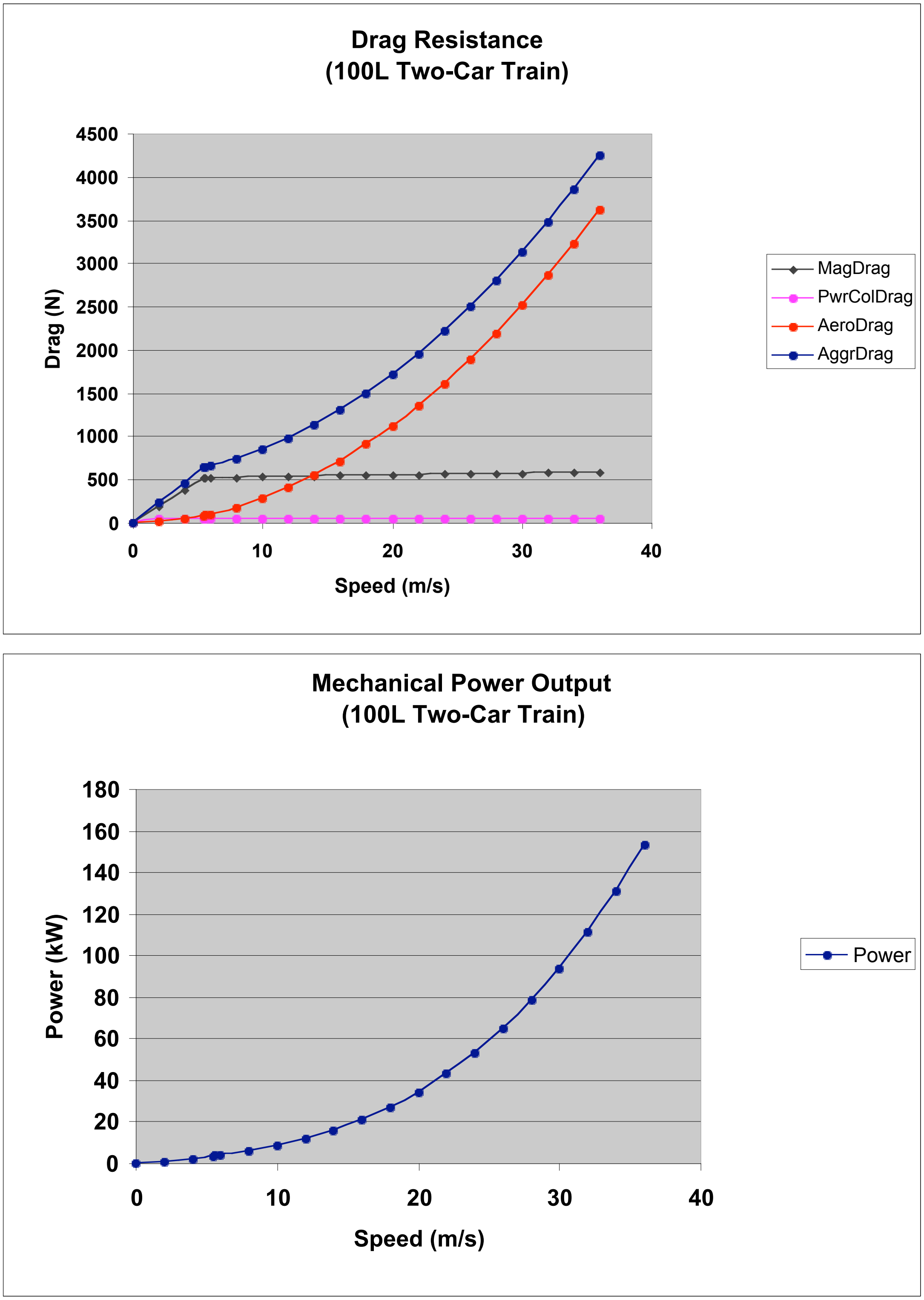


Figure 6-2. Drag and Power Characteristics of the CHSST 100-L

6.3 Propulsion Requirements and Characteristics

6.3.1 System Configuration

The CHSST is configured with two single-sided linear induction motors (LIM) each built up from modules with a resultant series-parallel configuration. The LIM stator is a conventional laminated iron structure with aluminum windings. The guideway mounted reaction rail is a thin aluminum plate with back iron. The back iron is also part of the magnetic circuit for both guidance and levitation. A cross-section view of the LIM stator and reaction rail is shown in the Aichi Prefecture report. The 100-L vehicle has five modules per side and the 100-S vehicle has three modules per side. Each LIM section weighs 175 kg and has a nominal rating of 130 kVA. The IGBT power electronics inverter for powering the LIM weighs 400 kg and is configured as a two-section inverter for each 100-L vehicle and as one two-section inverter for each pair of 100-S vehicles. The LIM and its power electronics represent less than 15% of the vehicle weight.

The nominal air gap for the LIM is about 14 mm between the bottom of the stator surface to the top of the reaction rail surface. Estimated improvements in performance with reduced gaps are reported in a section of Table 3-1 of the Aichi Prefecture report. An estimated improvement of 3-4% increase in thrust is estimated for each mm reduction in gap. For example, reducing the LIM gap from 14 mm down to 10 mm (which would translate to a corresponding increase in the levitation gap of from 6 mm to 10 mm) should increase thrust capability by about 15%, but at a cost of additional levitation power.

6.3.2 LIM Design Requirements

The design criteria for the LIM requires that it be capable of developing the minimum thrust required to satisfy the requirements calculated in Equation (6-5), given the available installation and size and weight constraints of the vehicle. Additionally, maximum headwinds as well as grade climbing capability must be factored into the LIM's design requirements. Table 6-3 lists some of the key selected performance characteristics and corresponding thrust force requirements for the 100-L three-vehicle train assuming a maximum speed of 36.1 m/s (130kph) and the other requirements as listed in Tables 6-1 and 6-2 above.

Table 6-3. Selected Thrust Force Requirements for the 100-L Three-Vehicle Train

Characteristic	**Value**	**Required Thrust Force (N)**
Max Initial Acceleration	1.11 m/s^2 (4.0kph/s)	84,900
Max Speed @ 25m/s Headwind	36.1 m/s (130 kph)	12,530
Grade Climbing Capability	7%	53,495

A LIM and its associated power electronics sized for simultaneously meeting all of the above requirements would have to produce a thrust force of more than 150 kN. However, because of size, weight, and cost considerations the more conventional design approach is to size the LIM for high thrust at low speeds and for high power at the higher speeds. Grade climbing capability tends to complicate this somewhat, particularly when having to design for constant speed operation while on a gradient.

6.3.3 Performance Capability and Operating Characteristics

MUSA report [2] contains a LIM thrust capability curve for the 100-L vehicle for a 3-car train with a maximum weight of 78 tonnes. That curve is replicated here in Figure 6-3 as the "MaxThrust" curve. As shown, the curve has an approximate constant thrust of nearly 90 kN out to a speed of about 11 m/s (40 kph) and then the thrust falls off exponentially as shown.

Also shown in this figure is the curve captioned, the "TotalDrag" curve. This curve incorporates all of the elements given in Equation (6-5). It also includes the effect of a headwind condition of 25 m/s, but does not include the effects of a gradient. The curve, captioned here as the "AccelCap" curve, is the accelerating capability of the LIM taking into account all of the drag resistance requirements contained in the "TotalDrag" curve. The LIM develops sufficient thrust force to meet or exceed the 0.113g requirement given in the above table and can do so out to about 5 m/s (18 kph). Out to speeds of about 13 m/s (47 kph) the acceleration capability meets or exceeds 0.1 g.

At the extended 36 m/s (130 kph) point the thrust capability just meets the thrust demanded for operation with only a small accelerating capability remaining. Again all of the results discussed here are for operation on a zero gradient.

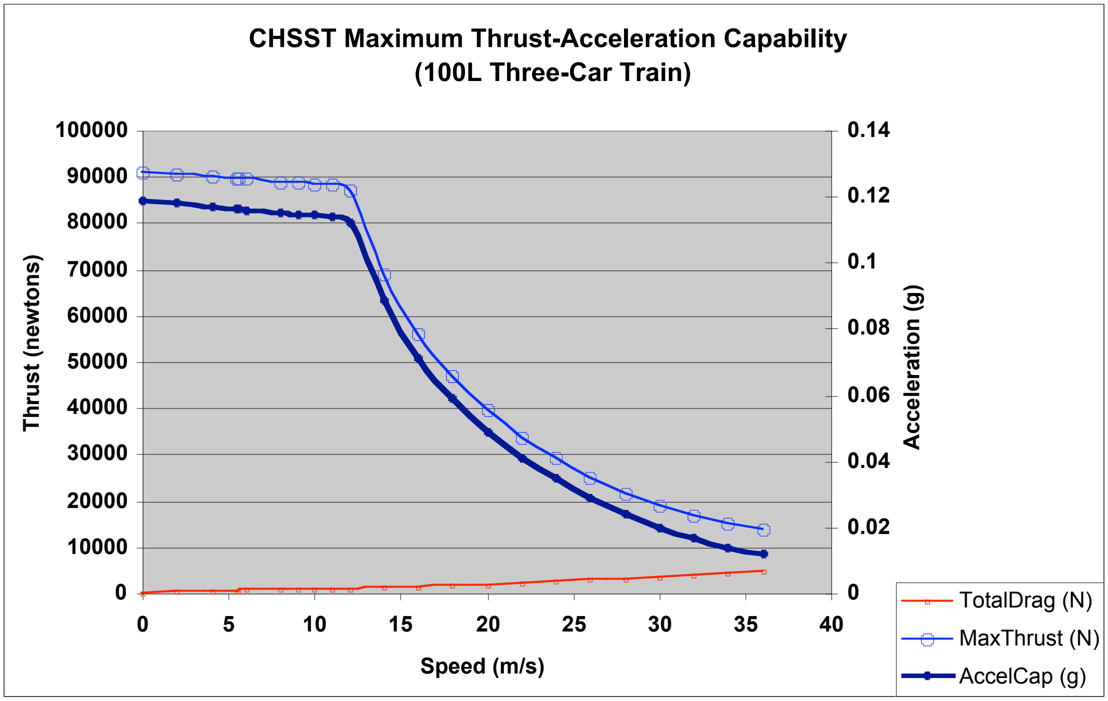


Figure 6-3. CHSST 100-L Maximum Thrust-Acceleration Capability

6.3.4 LIM Power Characteristics

Selected LIM input electrical characteristics for the 100-L three-vehicle train are given in MUSA Report No. 1. Figure 6-4 shows the mechanical output power capability (kW) and the corresponding required input power in kVA for the maximum thrust condition.

As seen from Figure 6-4, the CHSST propulsion system does not operate in a constant power regime beyond the breakpoint. speed point shown. This is apparently the consequence of how the LIM is controlled. The LIM operates in a variable voltage-variable frequency mode, for which there are at least two control philosophies that can be applied. One control approach is to operate with a constant percentage slip, which is typified by a constant volts/hertz mode of operation. The other approach is to operate with a constant slip frequency. The CHSST operates in this second mode with the further constraint that the maximum input voltage to the LIM is reached at the breakpoint speed. The consequence of all of this is that as shown in Figure 6-4, the LIM does not operate in a constant power mode beyond the breakpoint speed and in fact its maximum power point occurs at the breakpoint.

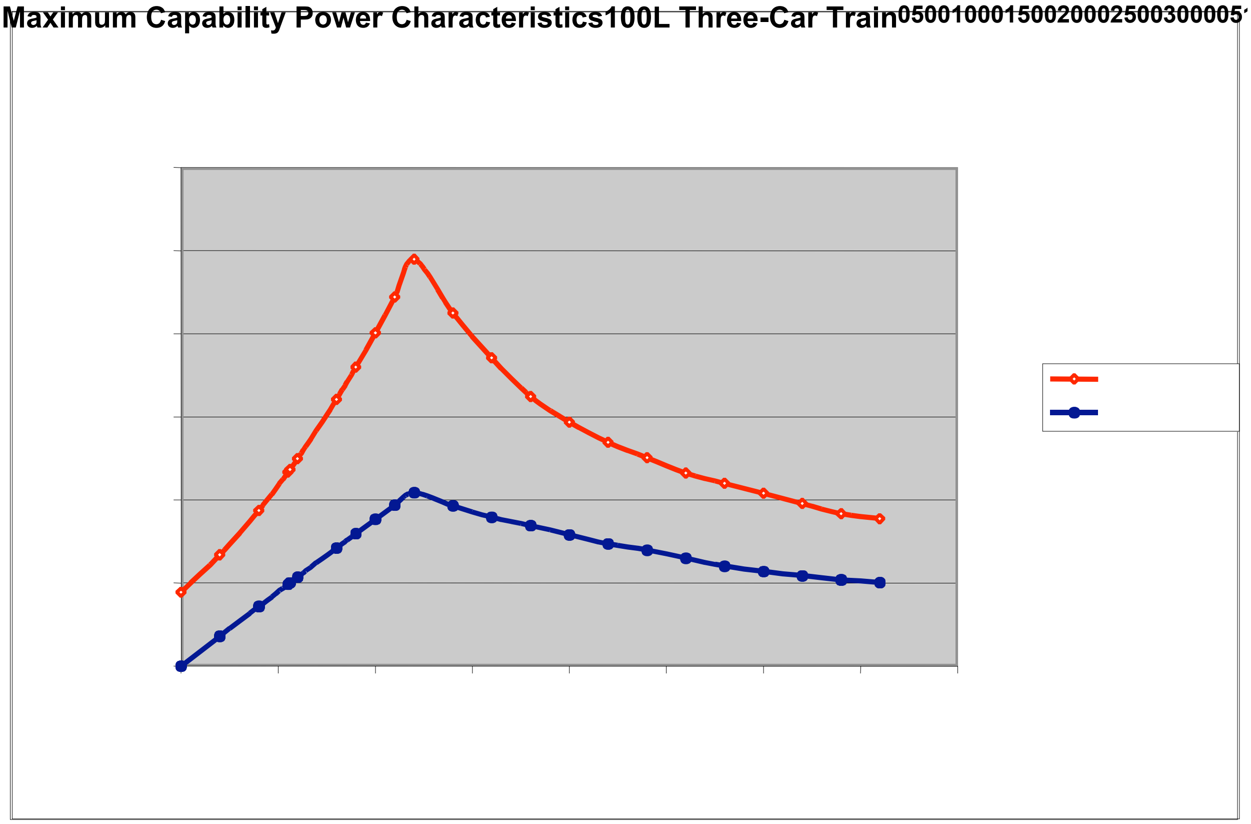


Figure 6-4. Maximum Capability Power Characteristics for 100-L Three-Car Train

The data contained in the MUSA report is not sufficient to enable one to discuss the efficiency and power factor characteristics of the CHSST LIM. However, during our meeting with Chubu, a maximum capability performance table for the 100-S LIM was made available to the FTA team. Figure 6-5, which has been derived from that table shows the power characteristics for a single LIM section for the 100-S vehicle, and it is our understanding the LIM used on the 100-L is similar to it.

As shown here, the input and output power characteristics are similar to those discussed earlier for the 100-L. Note also that Figure 6-5 does show Chubu's estimates of LIM power factor and efficiency. The shapes of these curves are typical for the LIM; that is, a maximum power factor at zero speed and then decreasing with increasing speed (load), and an efficiency that increases with speed (load). More specifically for the CHSST LIM and at the design point speed of 110.0 kph (30.6 m/s), the estimated power factor and efficiency are 57% and 75% respectively.

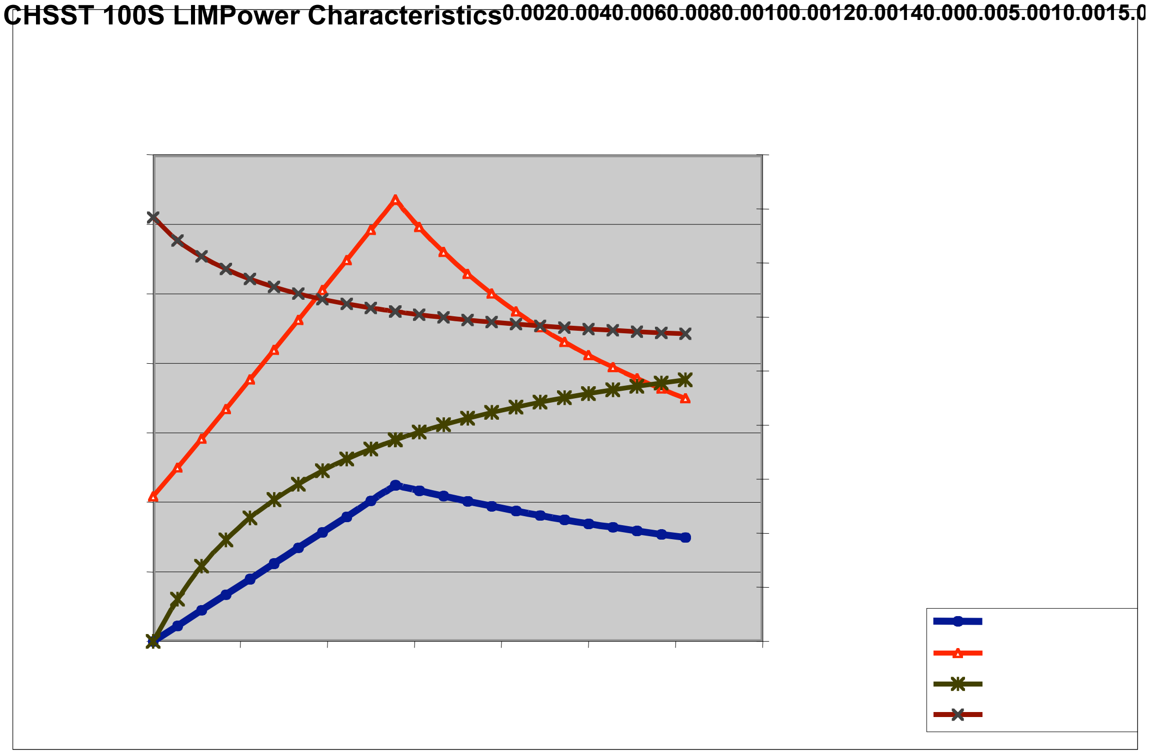


Figure 6-5. CHSST 100-S LIM Power Characteristics

6.4 Power Supply and Collection

6.4.1 Configuration

The CHSST operates with a DC power supply connected to solid trolley rails. The nominal trolley rail voltage is 1500 Vdc. The propulsion system is capable of operation with trolley rail voltages down to 900 V where system shutdown is supposed to occur. Based on the data made available for our review, full system performance should be available with a trolley rail voltage drop of about 400 V (more than a 25% voltage drop) from the nominal voltage setting.

Based on the data made available for our review, full system performance should be available with a trolley rail voltage drop of about 400 V (more than a 25% voltage drop) from the nominal voltage setting. Operational capability over this voltage range is consistent with other modern dc transit systems and should also work for well spaced out rectifier traction substations. The trolley rails are insulated above ground and are exposed on each side of the guideway beam. For minimum wear, the trolley rails use stainless steel cladding over the aluminum conductors.

The power collectors, one for each of the insulated power rails, are located on each vehicle and consist of a set of contact brushes. The CHSST power collector configuration represents relatively standard technology for contact power collection, so achieving speeds of up to 160 kph (44.4 m/s) and well beyond does not represent any particular technological challenge. Input L-C filters are located on the vehicle at the input to the LIM inverter. These weigh about 240 kg; for the 100-L configuration one filter has the storage capacity to handle a three-car train. For the 100-S configuration, one filter can handle the storage capacity requirements for a four-car train.

6.5 U.S. Mandatory and FTA System Requirements

With respect to the mandatory requirements of fire safety, noise, magnetic and electromagnetic fields, ADA, etc., most of these are system level issues with no direct impact to the propulsion system. As part of MUSA's Americanization effort of the CHSST, the propulsion system would be expected to meet those codes and standards as outlined in MUSA Report No. 2 [5]. A comparative review of the current Japanese codes and standards, for which the existing CHSST is built, would seem to be beyond the scope of the evaluation being discussed here.

Table 6-4 summarizes the pertinent FTA system requirements, as they would relate to propulsion system design criteria. These requirements include not only speed related parameters—speed, acceleration and jerk—but also environmental/guideway constraints that influence propulsion system sizing and performance. The FTA requirements as shown were originally developed as a generic set of specifications intended to satisfy a broad set of urban type applications and was most likely not intended to be a firm set of requirements to be universally applied. It should be understood that these requirements may need to be modified to meet any site-specific topography and urban application constraints. As described in Chapter 4, an urban application with long distances between stations would certainly want to exploit the high-speed, high acceleration capability whereas a dense urban environment with close station spacing would make more use of the need for a tight turn radius and a lesser need for high-speed performance. Additionally, since grade climbing capability is perhaps one of the most demanding requirements in propulsion system sizing, having grade climbing capability in a propulsion system would make sense only for those systems that would require it.

Table 6-4. FTA System Requirements for Propulsion Sensitive Parameters

Parameter	**FTA Requirement**	**CHSST 100-L**	**CHSST 100-S**
Maximum Speed	160 kph	100 kph	110 kph
Longitudinal Acceleration	0.16g	0.11g	0.13g
Longitudinal Jerk	0.10 g/s	0.08 g/s	0.08 g/s
Grade Climbing	7% full performance	7 %	7%
Horizontal Curves	18.3 m	50 m	25 m
Vertical Curves	1000 m	1500 m	1000 m
Headwind	50 kph full performance 80 kph ride comfort threshold	90 kph	90 kph

The data shown for the CHSST 100-L and CHSST 100-S are those that have been published in the references cited in this report. With respect to maximum speed, the FTA team was informed during the Chubu site visit that both the 100-L and 100-S were designed for a speed of up to 130 kph. The thrust capability analysis done and reported on here has shown that each system can operate at or near such a speed. The team also was informed that increasing the speed to the 160 kph range would require a substantially new design.

Similarly, the team was informed that acceleration performance also could be increased to the 0.16 g limit with the understanding that the breakpoint speed from constant thrust to variable thrust would have to be reduced to stay within the power limits of the inverter. Although such a change appears to be a logical one, Chubu should provide the modified thrust performance curves. Changes to increase the jerk limit capability would appear to be a control system adjustment problem and should be achievable, but needs confirmation. The suitability of an equal value deceleration, for service braking capability, should also be confirmed, and is discussed further in Chapter 7.

6.6 Evaluation and Issues

6.6.1 Overall Observations and Impressions

The HSST is a mature technology at least with respect to the propulsion system. Linear induction motor propulsion was developed, demonstrated and evaluated more than a quarter century ago for both high-speed and low-speed transportation systems. Numerous test track and exposition-type systems for urban applications have been demonstrated. The power electronic controls also have matured during this time interval and such systems are now widely utilized in many industrial applications. As such, there is little technical risk to the eventual wide-scale deployment of LIM systems in an urban transit setting. The deployment issue is that a comprehensive set of system requirements must be known and understood and adequately defined in order to properly size the propulsion elements of the system.

The test program conducted by the Aichi Prefecture appears to have been a comprehensive program and seems to have addressed all of the key propulsion system issues. Unfortunately, the summary nature of the document provided to the FTA team to review has enabled only a cursory review of CHSST testing, as the report itself does not contain any of the source data, test results and subsequent analyses referred to in the summary report. Also, since all of the testing conducted and reported on has been with the limited size Nagoya test track, the opportunity for endurance type testing would appear to have been limited.

The observations made at the site visit in Nagoya were helpful in gaining a better understanding of CHSST and some key observations follow. With respect to the propulsion system it was noted that the test vehicle could not maintain its speed while on the 6-7% gradients of the test track. This will be discussed further in this evaluation. Noticeable jerk sometimes occurred during initial acceleration on some of the test rides, but this may have been more attributable to driver action rather than with problems with the control system per se. Nevertheless, appropriate jerk limits on acceleration will need to be demonstrated.

Power collector noise appeared to be minimal during our viewing of vehicle-passing tests. However, the power or trolley rails are exposed as they are on the outboard sides of the guideway. These rails are located along each outside surface of the guideway girders and under the running surface. This may require some sort of guarding to prevent the possibility of electric shock in those locations where the guideway may become accessible to the public.

6.6.2 Linear Induction Motor Operating Characteristics

As noted here, the single-sided LIM with back iron develops an attractive force between the LIM surface and the reaction rail. As a point of reference, the LIM capabilities table for the single LIM section previously discussed shows a maximum thrust force of about 3234 N and a concurrent lift force of about 1860 N. Furthermore, this 57% ratio of lift to thrust force is relatively constant over the entire speed-thrust range shown in the table. Because of the way propulsion and levitation are configured, the lift force produced by the LIM is in a direction to oppose the levitation force, thus requiring the levitation system to buck out the LIM lift force. The net effect of this is that the LIM lift force reflects itself as a slight increase in vehicle weight as far as the levitation system is concerned. It is unknown the extent to which Chubu has investigated whether an orientation change to the installation of the LIM, in order to provide an assist to lift, would be beneficial or not. Additionally, any changes in the nominal air gap on either the LIM or levitation side would affect this aspect.

Also as noted here, the control philosophy chosen for the LIM of the CHSST is to operate the LIM in a constant slip frequency mode as opposed to a constant slip mode. Although these sound the same they are really quite different. The constant slip frequency mode runs at certain slip frequency such as12 HZ, and this frequency is held constant through the operating frequency (and speed) range. In the constant slip mode, for example a 10%

slip results in a variable slip frequency whose value depends upon what the operating frequency happens to be. At this point in the evaluation, we have been unable to review Prof. Nonaka's published work on the CHSST LIM development and the rationale for Chubu adopting the constant slip frequency control philosophy. Its choice may have compromised the performance capability of the LIM, although that is not known with any certainty. It would appear that operating the LIM in a constant slip and constant volts/hertz mode should enable the LIM to produce a constant output power above the maximum thrust breakpoint rather than the decreasing power characteristic that is shown in Figure 6-5 above. However, to exploit this constant Volts/Hertz mode and still use the existing LIM requires a power supply voltage closer to 3 kV rather than the current 1.5 kV supply. Further comments on this would really require a more thorough review of the design basis for the LIM and its controls and further discussions with Chubu.

6.6.3 Grade Climbing Capability

The presently configured CHSST has limited constant speed-grade climbing capability. Figure 6-6 illustrates this problem. The total drag resistance shown here is for the 100-L three-car train for the case of a 25 m/s headwind. The "TotalDrag" curve shown here is represented by Equation (6-5) for the case of a 25 m/s headwind and should represent a worst-case condition. Note that steady-state operation will occur where the total drag curve intercepts the maximum capability curve. For a grade of 2% that intercept occurs at slightly more than 26 m/s (94 kph). This means that if a vehicle is operating at any speed greater than that speed, the vehicle would have to slow down until it intercepts the maximum drag curve, which of course is the only stable operating point. Some sample cases for other grades are shown in Table 6-5.

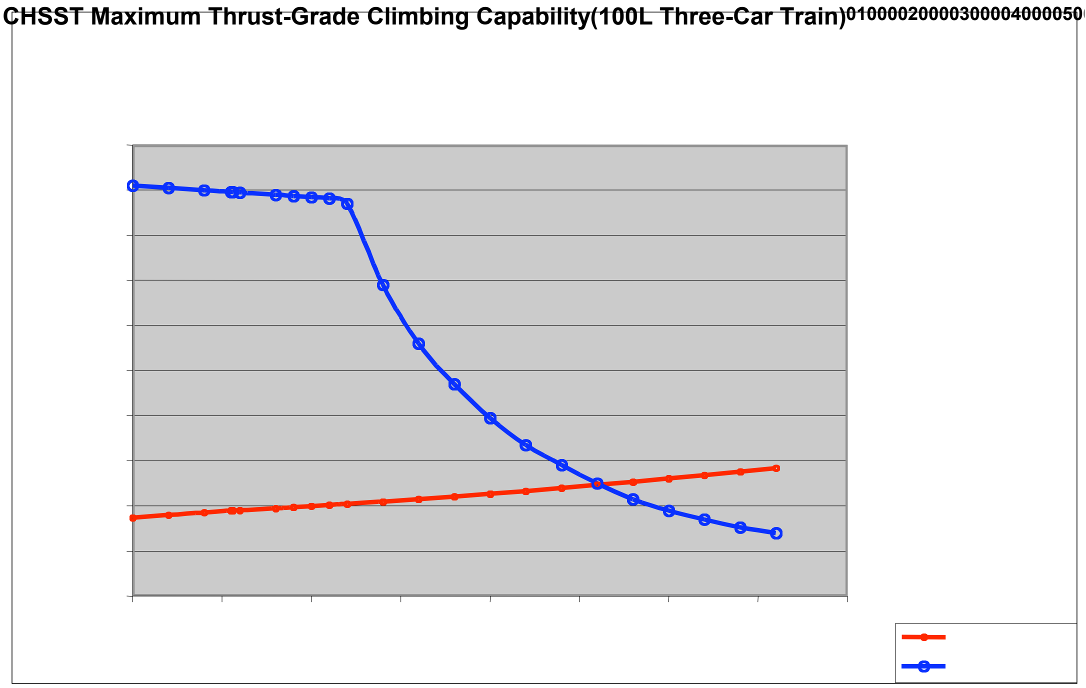


Figure 6-6. Maximum Thrust-Grade Climbing Capability for a 2% Grade

*Table 6-5. Grade Climbing Capability for the CHSST 100-L Three-Car Train**

Grade (%)	Steady-State Speed
1	30 m/s (108 kph)
2	26 m/s (94 kph)
3	23 m/s (83 kph)
5	19 m/s (68 kph)
7	15 m/s (54 kph)
10	12 m/s (43 kph)
*25 m/s headwind	

As shown here the steady-state velocity for a 7% grade is only 15 m/s (54 kph). Under conditions of no headwind, as expected, the steady-state operating point increases only slightly to about 16 m/s. This means that the CHSST in its present configuration is not likely to be suitable for a hilly corridor if higher speed operation on the corridor is required. Several possible solutions to providing more grade-climbing headwind capability would include operating the LIM in a constant power mode. For this particular case the peak power developed at the breakpoint as shown in Figure 6-5 is slightly greater than 1000 kW compared to the 650 kW being developed at 15 m/s for the present control approach. For the hilly corridor situations, one should also consider the possibility of using a copper winding for the LIM rather the presently used aluminum winding, as well as possibly also increasing the power capacity of both the LIM and the inverter.

Although not explicitly stated in the FTA requirements, vehicle weight is perhaps one of the most critical elements of a maglev system, particularly to a system with onboard propulsion. The 100-L has a 17,500 kg single-vehicle weight and for the 100-S a corresponding weight of 9,000 kg. These weights in conjunction with their payload weights of 10,500 kg and 6,000 kg respectively impose severe design constraints on both the propulsion and levitation systems. Any weight reduction that can be achieved with the vehicle has a multiplier effect on both levitation and propulsion, since a vehicle weight reduction can also reduce the weight of levitation and propulsion, which in turn means a further reduction in overall vehicle weight.

The CHSST vehicles, given their overall size, exclusive of levitation and propulsion, appear to be heavy for maglev systems. In order to meet U.S. mandatory and FTA performance requirements, Americanization of the CHSST will not only be desirable but may be required. Any planned Americanization effort of CHSST should address innovative vehicle designs that have significant weight reduction as an objective, as well as meeting any crashworthiness requirements as an additional factor.

7 Braking System

7.1 Braking Modes

The CHSST has three independent and redundant braking modes and utilizes both electrical and mechanical brakes. These brakes operate either independently or in conjunction with each other. The first braking mode is electric service braking using the LIM, and the second is the hydraulically controlled mechanical brakes. The third braking mode is on the landing skids, in which the vehicle is de-levitated. This normally occurs only in the event of an emergency, where all other brakes have either failed or are not available.

The electric service brakes themselves operate in one of two modes dependent upon vehicle speed. The first mode is the regenerative mode, which normally operates at the higher vehicle speeds and the second mode is the dynamic brake mode, which normally operates at the lower speeds. In the regenerative mode, the energy produced by the kinetic energy of the vehicle is converted into electrical energy and is transferred to the trolley rails and power supply for use by other electric loads. In this mode, the linear induction motor (LIM) is controlled to operate as an electric generator converting vehicle's mechanical energy into electrical energy. In the dynamic braking mode, energy is supplied by the power supply and trolley rail and is dissipated within the LIM, which operates in the plugging or reversed phase mode.

The mechanical brakes are hydraulically controlled caliper brakes in which redundant and independently controlled hydraulic power sources are located on each vehicle. The calipers grip the outer rail flange. One of the hydraulic power sources is used for normal service braking and the other as an emergency back-up power source. The mechanical brakes are also used as the parking brake.

From high-speed operation, the normal braking sequence is to first apply electric brakes. At a lower speed the mechanical brakes are blended in and braking becomes fully mechanical at very low speeds. The various speeds at which these braking sequences occur are based on the relative energy efficiency as well as the effectiveness of each braking mode and will be further discussed in this section.

7.2 Design Basis

7.2.1 System Level Requirements

Table 7-1 summarizes the CHSST principal top-level system requirements with respect to the system braking design criteria as described in MUSA Reports [2, 3], and as supplemented by the information received during the FTA's team visit to Chubu. The requirements as shown are applicable for all of the operational and environmental characteristics previously discussed in Section 6 above.

Table 7-1. Selected Braking Requirements

Requirements	**Specification 100-L**	**Specification 100-S**
Maximum Deceleration-Service Braking	1.11 m/s^2 (4.0 kph/s)	1.11 m/s^2 (4.0 kph/s)
Maximum Deceleration-Emergency Braking	1.25 m/s^2 (4.5 kph/s)	1.25 m/s^2 (4.5 kph/s)

7.2.2 Deceleration Rate Performance Characteristics

The general form of the drag resistance equation (D_T) including the effects of gradients and acceleration can be written as:

$$D_T=D_m+D_c+D_a+D_G+D_A \qquad \text{(newtons)} \qquad (7\text{-}1)$$

where the D_m, D_c, D_a, terms were defined by Equations (6-1) through (6-44) in Section 6 of this report. The equations for the effects of gradients and acceleration are:

$$D_G=N(M \cdot g)\sin(\square) \qquad \text{(newtons)} \qquad (7\text{-}2)$$

$$D_A=N(M \cdot a) \qquad (7\text{-}3)$$

where N is the number of vehicles in a train, M is the mass of the vehicle in kg, g is the acceleration constant due to gravity (9.806 m/s^2), and $\square=\tan^{-1}(G/100)$, where G is the gradient expressed as a percentage and a is the acceleration expressed in m/s^2. (This term can also be expressed in gs where a must then be divided by the acceleration constant g.)

In the braking mode we should recognize that the drag resistance forces given by Equation (7-1) now become braking drag forces, that is the D_A becomes zero because we are decelerating, and the remaining terms in Equation (7-1) serve as retarding forces upon the vehicle. For a specified deceleration rate (d) the additional required braking force D_B can be determined as:

$$D_B= N(M \cdot d)-(D_m+D_c+D_a+D_G) \qquad \text{(newtons)} \qquad (7\text{-}4)$$

where again d is expressed in m/s^2 or expressed in gs when it divided by the acceleration constant.

Braking distances can be determined from kinematics relationships. For the special case where the deceleration is held constant over the entire braking interval and where V_i and V_f are the initial and final velocities respectively, the braking distance (S) can be estimated as:

$$S=(1/2d)(V_f-V_i)^2+(V_i/d)(V_f-V_i) \qquad (7\text{-}5)$$

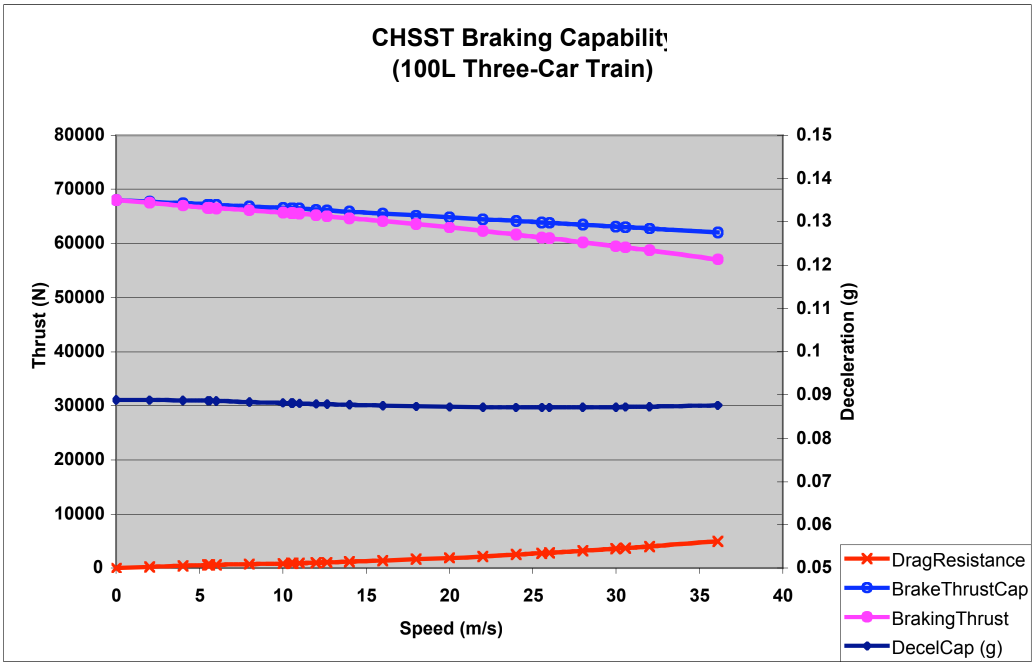
For the more general case where the deceleration is not constant but time varying, the kinematics equations, $V=d \cdot t$ and $S=(1/2)d \cdot V^2+V \cdot t$, must be solved in small delta-velocity increments by setting $\square t=(V_f-V_i)/d_{avg}$ where d_{avg} is the average deceleration rate over a small (V_f-V_i) interval.

7.2.3 Electric Braking Requirements and Characteristics

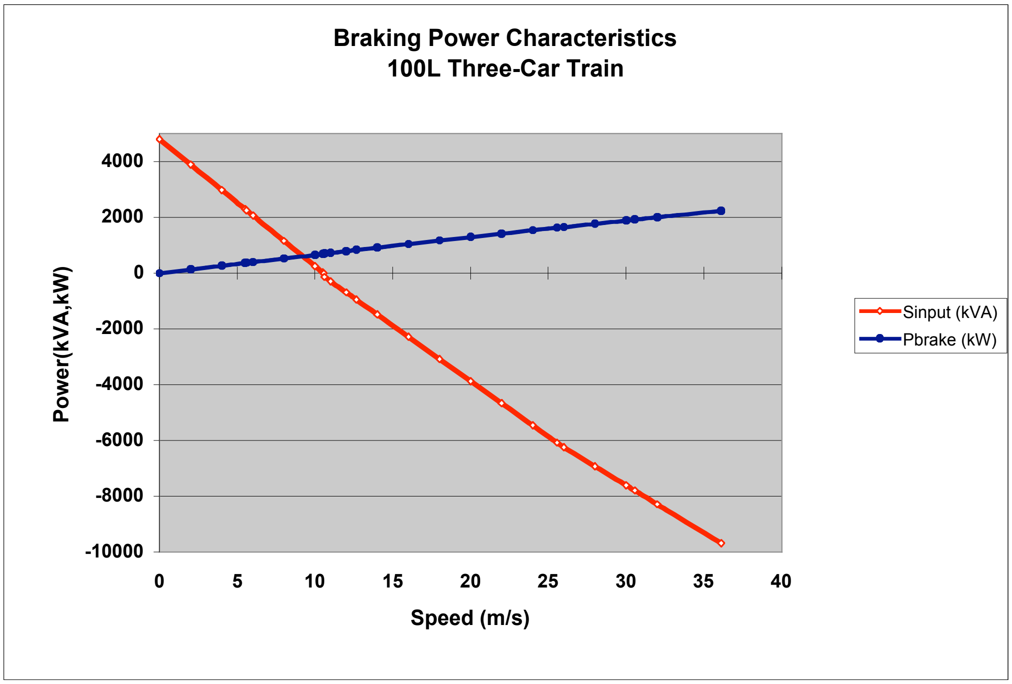
The electric braking characteristics of the LIM for a particular braking rate of 3.0 kph/s (0.085g) are given in MUSA Report [2] for a 78 metric tonne, 100-L three-car train. They are summarized here in Figure 7-1(a). The curve shown here is for the assumption that electric braking is being utilized throughout the entire speed regime and is for the case of a constant LIM current of about 300 A. As seen in the figure, the braking thrust capability curve varies from about 63 kN (14,180 lb) at 30.6 m/s (110 kph, 68 mph) to about 68 kN (15,300 lb) at zero speed. Also shown on the figure is the three-car train drag resistance for a 25 m/s headwind and zero gradient previously discussed in Section 6. The net difference between these two curves is the braking thrust curve (captioned as "Braking Thrust"), which varies from about 57 kN (12, 800 lb) at the highest speed shown of 36.1 m/s up to the 68 kN point at zero speed. The calculated deceleration rate shown here is approximately 0.09g over the entire speed range and slightly exceeds the specified 0.0856 g rate.

Figure 7-1(b) shows the mechanical output power required for the braking rate specified above. This power varies from just under 2000 kW at the 110 kph speed point down to 0 kW at zero speed. As shown, the input electrical power demand in kVA is either negative for regeneration where power is flowing from the inverter to the power rails and on to the rectifier substation for use by other loads, or is positive for dynamic (plugging) braking where power is being drawn from the rectifier substation and is consumed in the LIM. At the 110 kph speed point the power demand is nearly -8000 kVA (regenerative) and at the zero speed point is nearly +5000 kVA (dynamic).

The speed where the power demand approaches zero is at the approximate 38 kph speed point where the braking profile transitions from regenerative to dynamic. Since the LIM functions as an induction generator during regeneration it requires a source of excitation, which in this case is derived from the LIM inverter and vehicle input filter. It should be noted that different inverter-filter characteristics would result in different transition speed points. Extrapolating the data shown here to the Chubu specified maximum deceleration of 0.127g (4.5 kph/s) would result in a maximum braking power demand of more than 2400 kW at the 110 kph speed point and an input power requirement varying between about –9000 kVA for regenerative braking to about +6000 kVA for dynamic braking assuming no change in LIM excitation.



(a)



(b)

Figure 7-1. Braking Characteristics for the 100-L Three-Car Train

7.2.4 Mechanical Brake Requirements and Characteristics

Although intended to operate as a supplement to the electric brakes, the mechanical brakes are designed to have the capability to repetitively and safely stop a vehicle from maximum speed. At some minimum speed point where electric braking loses its effectiveness and is disengaged, the mechanical brakes then are intended to function as the sole means for safe braking. As stated in the Aichi Prefecture report [1], allowable brake pad wear of the caliper brake pads is 5 mm, and the allowable wear for the emergency landing copper powder alloy skid is 2 mm.

The mechanical braking system consists of calipers that clamp on to the vertical surfaces of the reaction rail iron. As described in MUSA Report [2], the calipers are hydraulically controlled and the system operates with brake pressure control. The hydraulics operate at a pressure of 210 kg-f/cm^2 (2990 psi). The hydraulic section principal components consist of the hydraulic pump, primary and standby accumulators, and pressure control section. The hydraulic pressure range is design to operate between 185 kg-f/cm^2 and 210 kg-f/cm^2 (2630-2990 psi). The pressure control section has three major elements; service brake pressure control, emergency brake pressure control and standby brake pressure control. Pressure switches are installed at the accumulators and regulate the pressure levels of both the primary and standby hydraulic systems. For the 100-L configuration, six of the ten LIM modules are equipped with the caliper brakes and for the 100-S four of the six modules are so equipped.

7.3 Operational Experience

According to the Aichi Prefecture report [1] CHSST braking performance was extensively tested and reported on in several sections of Table 3-1 of the report. The following summarizes the relevant CHSST test experience.

Electric Brakes**.** Reported braking deceleration rates from high-speed operation appear to be affected by LIM end effects, although the extent to which this effect impacted braking performance was not elaborated upon. For a fully loaded (100-S) vehicle, initial decelerations achieved varied from 4.3-4.4 kph/s (0.122-0.125g) from 100 kph speeds. Below 50 kph and with supplemental mechanical braking applied, higher decelerations of 6.5 kph/s (0.18 g) were reported.

Decelerations of about 0.14 g at 95 kph were reported for the empty vehicle condition. Reference also was made to some LIM control issues, the need to limit LIM current (and thus limit braking effort), and concerns about trolley voltage magnitude increases at speeds approaching 100 kph.

Performance for the emergency braking mode in which both electrical and mechanical brakes were used indicated an achieved deceleration rate in the range of 5.4-5.7 kph/s (0.153-0.162g) from speeds of 100 kph and corresponding braking distances of 250 m or less. Similar results were reported for the case where emergency braking was achieved with the electrical brakes disabled and only the mechanical brakes being available.

Mechanical Brakes**.** Tests were conducted to simulate electrical brake failure where all braking then relied upon the mechanical system. For a fully loaded vehicle (100-S) condition and at 100 kph, a braking distance of 299 m (987 ft) and an average deceleration of 4.65 kph/s (0.132 g) were reported. Similar test results were reported for an empty vehicle condition.

Brake pad wear from 100 kph braking speeds was reported to vary from 0.06 mm to 0.76mm depending on the specific location on the vehicle of the brake pads. The average wear for an emergency braking cycle was found to be about 0.18 mm. Although this would enable 28 emergency braking cycles based on the 5 mm wear rate design criteria, CHSST adopted the number of allowable emergency braking cycles before brush change-out to be about 18 cycles.

Landing Skids**.** Wear measurements for landing skid wear for a fully loaded (100-S) vehicle in a de-levitated condition was performed and showed that skid wear from an emergency braking operation from 100 kph to a full stop was about 0.71-0.75 mm per cycle. This indicated that the CHSST could tolerate at least two emergency braking cycles from a high-speed condition before requiring replacement of the skid wear surface. Emergency braking tests from speeds lower than the 100 kph condition showed somewhat less wear on the skids. For example, the Aichi report states that in the speed range of 10-49 kph up to 16 emergency braking cycles could be tolerated, but above 50 kph not more than 2 cycles should be expected. Emergency braking deceleration rates were not reported so the potential impact to passengers is unknown.

7.4 U.S. Mandatory Requirements and FTA System Requirements

As stated earlier, with respect to the mandatory requirements of fire safety, noise, magnetic and electromagnetic fields, ADA, etc., most of these are system level issues with no direct impact to the braking system with the exception of safety. The braking system is a safety critical system and its design and operation must be demonstrated to be fail-safe. The nature of the independent and redundant brakes answers only a part of the safety critical issue; as a minimum a systems safety assessment including a hazards analysis, and failure modes and effects analysis should be performed and the fail-safe operation verified.

Table 7-2 summarizes the pertinent FTA system requirements, as they would relate to braking system design criteria.

Table 7-2. FTA System Requirements for the Braking System

Parameter	FTA Requirement	CHSST 100-L	CHSST 100-S
System Configuration	Independent and Redundant	Three Separate Systems	Three Separate Systems
Deceleration, Normal	0.16g	0.113g	0.113g
Braking Emergency	0.36g	0.127 g	0.127 g
Gradeability	7% full performance	7 %	7%
Horizontal Curves	18.3 m	50 m	25 m
Vertical Curves	1000 m	1500 m	1000 m
Headwinds and Tailwinds	50 kph full performance 80 kph ride comfort threshold	90 kph	90 kph

The FTA requirement for both normal and emergency deceleration is based primarily on the necessity for the close headways and vehicle spacing associated with the requirement for 12,000 passengers per hour per direction (pphpd) as well as the need for frequent service. For urban service these requirements should result in headways of the order of 120 s or less which in turn will result in relatively close vehicle spacing. For example, 200 passengers in a train would result in an average headway of about 60 seconds per train for a throughput of 12,000 pphpd. A corresponding spacing of about 600 meters would be necessary if the average speed was 10 m/s. For the same conditions, operating 100-passenger trains result in train spacing of 300 m and headways of 30 s, and operating 400-passenger trains results in spacing of 1200 m between trains and a corresponding headway of 120 s. Note that these must be considered as average numbers only and headway and vehicle spacing would have to be tailored to the site-specific set of conditions.

With respect to evaluating the performance of a braking system with its safety critical requirements, a more meaningful metric would perhaps be the allowable braking distance. The following table compares the estimated braking distances that can be derived from the FTA requirement, assuming a constant deceleration rate, and compared to the CHSST 100-S test experience. The FTA estimates given here are based only on the kinematics considerations previously discussed and do not add to the braking distance any control system delays.

Table 7-3. FTA and CHSST Comparative Braking Distances

FTA Requirement	Calculated FTA Braking Distance	CHSST 100-S Test Experience
0.16 g Normal	246 m	299 m
0.36 g Emergency	109 m	243 m

The CHSST data referred to here was extracted from the summary data contained in the Aichi test report. As a point of reference, a calculation of the expected braking distances assuming a constant deceleration mode of the Chubu stated performance of 4.0 kph/s for normal deceleration and 4.5 kph/s for emergency deceleration would have resulted in estimated braking distances of 347 m and 308 m respectively, compared to the measured values of 299 m and 243 m shown above. Therefore, the test data clearly demonstrates that the deceleration profile is not constant but apparently increases with decreasing speed, which seems to be consistent with the limited amount of information contained in the Aichi report. It is assumed here that the expected braking performance of the 100-L vehicle follows that of the 100-S version, although that should be verified.

Given the FTA requirements as stated above, there is a question as to the suitability of the CHSST for operation in the U.S. for the current "as is" design. It would appear that an upgrade in deceleration performance would have to be a necessary part of an Americanization effort. As seen from the above discussion on electric braking, a simple upgrading of the deceleration performance with the current design may require power ratings for both the LIM and its inverter that would probably be beyond the capability of the present design. Increasing deceleration performance of the LIM and its inverter will require a rather substantial increase in their power ratings and may well be beyond that which is presently available. An alternative to this could be to make more extensive use of the mechanical brakes, but then the philosophy of the desired independent and redundant braking subsystems would have to be addressed.

7.5 Evaluation and Issues

- The brake performance test program conducted by the Aichi Prefecture appears to have been a comprehensive program and seems to have addressed the key braking system performance issues. Unfortunately, the summary nature of the document provided to the FTA team to review has enabled only a cursory review of CHSST testing, as the report itself does not contain any of the source data, test results and subsequent analyses referred to in the summary report.

- Two principal observations were made as a result of our Chubu visit. The first is the quite noticeable noise of the caliper brakes when they engage and disengage the reaction rail iron surface when stopping on the 6-7% gradients. There was also a noticeable vibration when the brakes were released on the gradient and the vehicle began its initial movement. An explanation of this behavior by the CHSST/MUSA engineers is required.

- The second observation deals with the overall installation of the caliper brakes. As previously stated these brakes, because of the inherent nature of the caliper-type design must surround and react in a pinching action against the vertical sides of the reaction rail iron. We were informed during our Chubu visit that the allowable lateral offset of the reaction rail is only 2 mm, and this applies specifically to the vertical surfaces of the reaction rail iron. We were also informed that this tolerance must be maintained. The apparent reason for this is the concern that the caliper brake shoes would suffer damage for larger lateral offsets, as a larger offset would interfere with the brush assembly as the vehicle moves down the guideway. The cost implications to this design choice should be evaluated and perhaps alternative configurations assessed. The effects on curve negotiation for small radii should also be included in this assessment.

- The braking distance of the CHSST vehicles seems to be less than those implied in the FTA requirement. An upgrade in the deceleration performance will be needed to satisfy this FTA requirement. The upgrade does not seem to be straightforward, as it impacts the LIM and inverter.

8 Automatic Train Operation

8.1 System Architecture

The Automatic Train Operation (ATO) system implemented at the 1.5 km Nagoya test track for the HSST-100 is a variant of the HSST-04 and –05 tested at the Saitama and Yokohama Expositions. The HSST-05 was the first magnetically levitated train authorized to carry passengers in regular operations in Japan. This first operational control system used for the HSST-05 was designed for shuttling each train on a single track at the Yokohama Exposition. It provided automatic operation by indicating a control speed, which a driver was to follow. It also had an overrun protection function. The Yokohama Expo was operated on a 570 m long track at a maximum speed of 42 km/h. Although the HSST at the Yokohama Expo was operated with a 99.9% reliability and a 99.8% availability, it did not have the operational characteristics of an urban maglev system that would have to operate at 110 km/h with minimum headways of 100 seconds. Therefore, a cab-signal type architecture with an ATO backed up by an Automatic Train Protection (ATP) system was designed by Kyosan Electric Manufacturing, Co., Ltd of Yokohama, Japan.

This configuration, which is shown in Figure 8-1, was developed incrementally. It first included the overrun protection function in a point-control system using wayside mounted transponders in much the same way as was used in the Yokohama Expo [1]. It was then modified to a continuous control system using what CHSST terms a “pattern belt.” The current system was tested using a fixed-pattern ATP. However, according to the literature [16], elements of a moving block system were also developed that can follow the location of a preceding train, and determine the state of switches. Some verification experiments for these subsystems have been performed on the Nagoya test track, demonstrating their robustness for future application.

The system shown in Figure 8-1 may be classified into the following subsystems:

1. Signaling system
    a. Automatic Train Protection, which is essentially an Automatic Train Stop (ATS) using transponders (emergency braking)
    b. Pattern type ATS for normal service braking
    c. Speed detection equipment
    d. Continuous train detection with check-in/check-out
    e. Interlocking equipment
2. Operation system
    a. Program Train Operation (PTO) providing automatic train operation functions

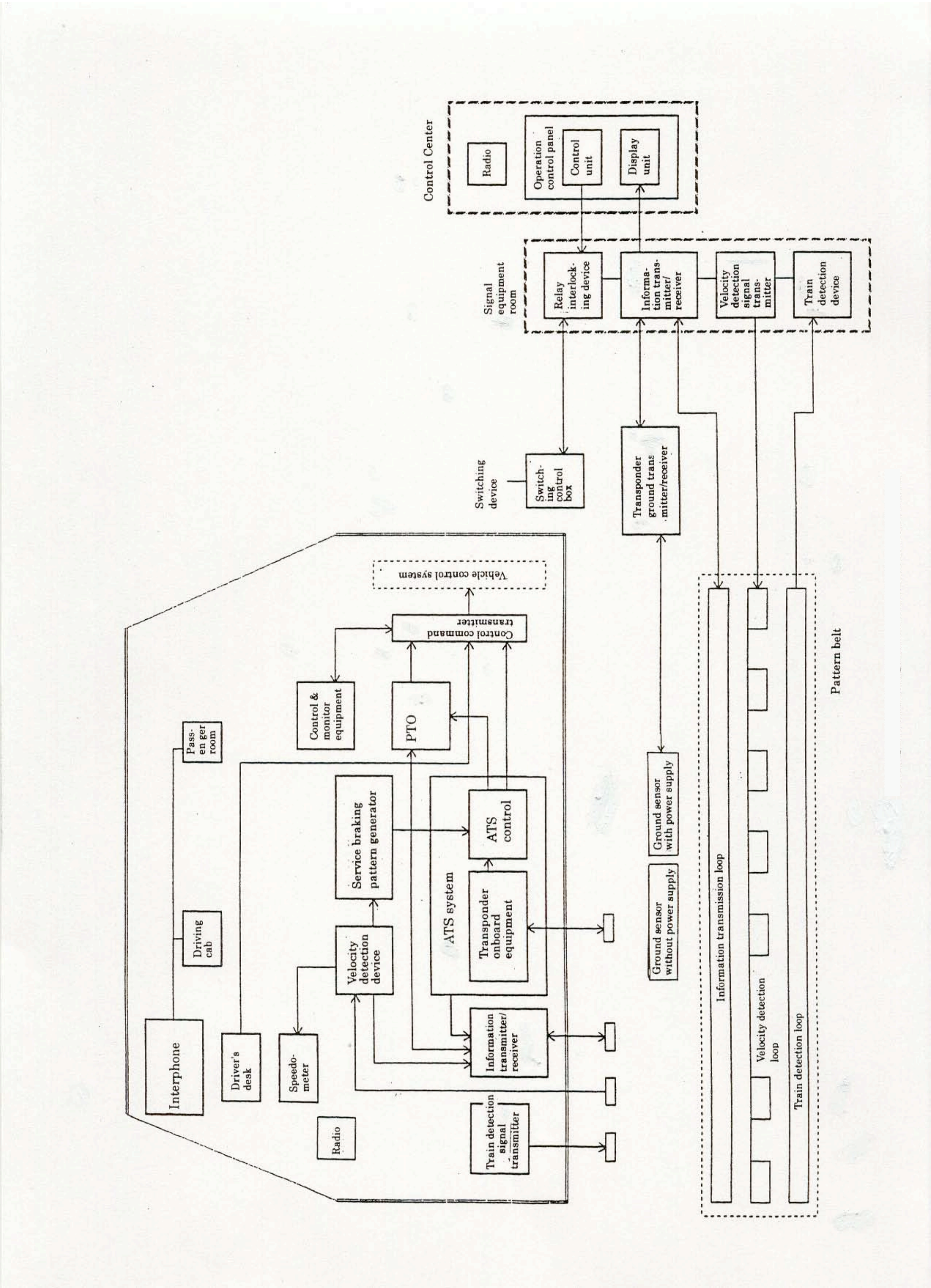


Figure 8-1. Configuration of signal communication equipment

    b. Manual Train Operation (MTO)
    c. Operation monitoring
    d. Car monitoring
3. Wayside-cab information transmission equipment
4. Wayside-cab supervision

Signaling control is provided by the Automatic Train Stop subsystem, which uses un-powered transponders for overrun protection. At the Saitama and Yokohama Expositions wherein each demonstrated a simple shuttle between two terminals, the wayside transponders without a power supply provided a safe, and simple economic signaling control subsystem. However, an urban system in which a number of trains are operated at reasonably close headways, it became necessary to incorporate a conventional continuous detection and control system. A conventional continuous control system requires fixed blocks in which the position of a train is detected in each block so that a permissible speed is set for each block thereby controlling operations. Therefore, a continuous pattern type ATS was introduced as a novel signaling control system, since only one train is operated at the test track. The continuous pattern type ATS was introduced with the consideration that it will be modified and improved into a moving block system in the future. Then operation of trains will be based on the location and speed of trains through wayside-cab information transmission.

Presence detection of the train is implemented by a conventional continuous-detection check-in/check-out system similar to other light and rapid rail systems. Train speed is determined by means of a velocity detection loop in the pattern belt that counts pulses and is intended to provide speed and stopping distance information on an absolute fail-safe basis.

8.2 Automatic Train Protection

The ATP subsystem performs blocking controls for intermediate blocks and also performs overrun protection functions via the pattern belt speed monitoring, so that a train can enter a station section at the highest speed possible. This is possible because the overrun allowance distance from a normal stop point to the absolute end is only about 10 m in length. In essence, this ATP is a simple Automatic Train Stop subsystem based on overrun protection being provided by wayside transponders. Safety is provided by the ATS, which finally applies the emergency brake to stop the train if it violates the speed limits pre-established between each pair of transponders. Figure 8-2 shows the full service braking pattern that is generated by the ATS from train speed information and measured distances between transponders. The points are controlled by a Type 1 electric relay interlocking device using train detection information. Continuous train detection check-in/check-out is provided by a continuous onboard high frequency signal that is received by the wayside train detection loop and is an element of the pattern belt. The normal service braking pattern generator shown in Figure 8-2. compares the normal service braking profile with the ATS speed limits to command the vehicle thrust and brake control system. The minimum range resolution of the service braking pattern is 60 cm at 110 km/h. The delay time for braking is 1.1 seconds; and the delay time for releasing the brakes is 1.2 seconds. These times are cumulative.

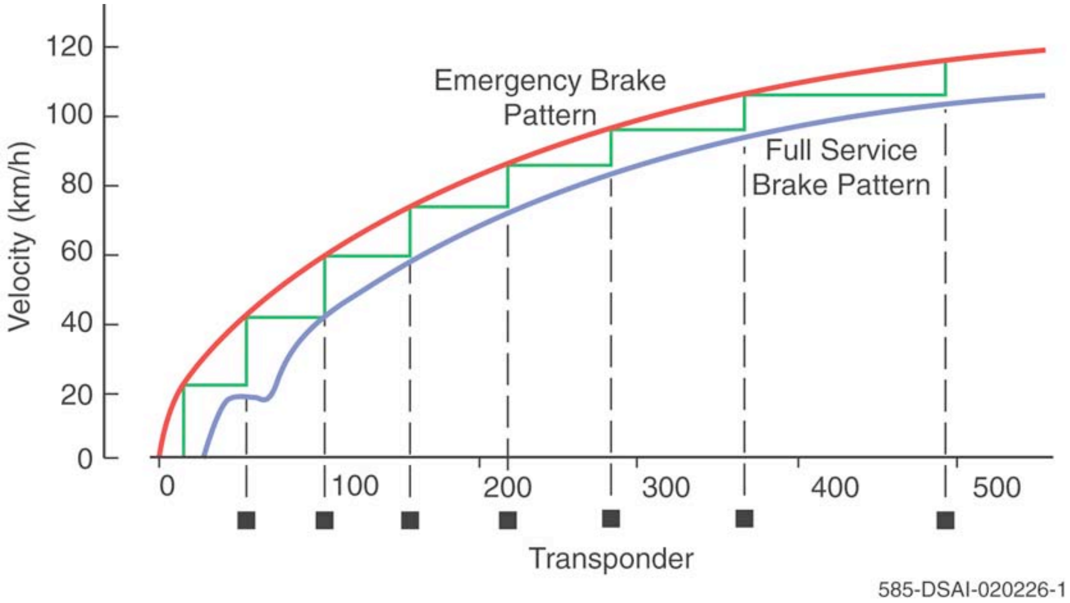


Figure 8-2. ATP Braking Pattern

The HSST test system is manually operated with the automatic train control assistance. The continuous pattern type normal service braking pattern (ATP/ATS) is continuously displayed on the operator’s console providing the operator with command speed information with which to follow. The operator can operate at a speed lower than the service braking pattern allows, but this will increase passenger trip time and reduce productivity. The human to machine interface console has been designed to supply minimum essential information to follow the central control authority commands. The actual speed is displayed digitally and as a conventional speedometer that can be compared to the speed limits in each section, which are displayed on the outer ring of the speedometer.

8.3 Speed Detection

Speed detection and absolute distance detection use the pattern belt. The wayside pattern belt antenna has openings in 30 cm intervals that mate with three vehicle antennas each located 20 cm apart as shown in Figure 8-3.

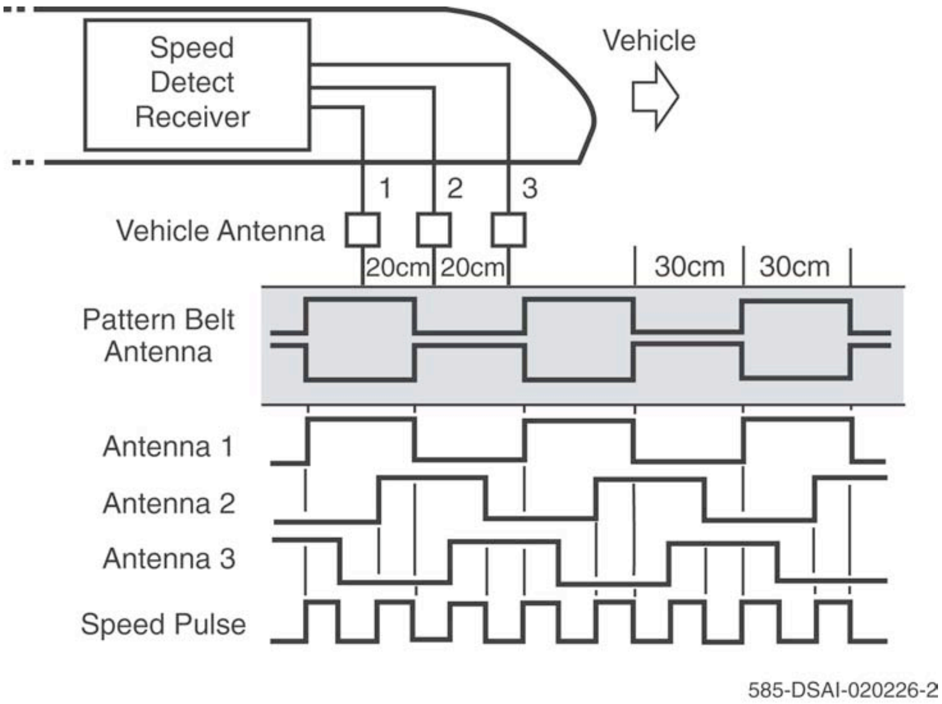


Figure 8-3. Speed Detection Pattern

Three speed ranges are used to construct the detection logic to achieve a reasonable accuracy of detection. The minimum detection speed is 0.5 km/h (0.139 m/s). Pulses of 10 cm in width are used for the speed range of 0.139 – 0.333 m/s. Pulses of 20 cm in width are used for the speed range of 0.333 m/s – 1.0 m/s. Above 1.0 m/s pulses of 60 cm are used. Phases from the vehicle borne system of three antennas are compared to verify the logic and to determine movement in the reverse direction. There is a dual set of redundant antennas on board to eliminate missing signals in a turnout area and to improve reliability. The relationship of speed vs. pulse frequency is given by the following:

f [Hz] = K V [km/h], where K = 2.778

The absolute distance detection subsystem counts these pulses and accumulates these pulses through (*an un-described*) fail-safe process. These pulses are the essential information for the continuous pattern belt ATP/ATS and moving block system. To ensure that spurious signals from either passing trains or turnout interference does not cause a distance measurement error, transponders have been superimposed in each block or section for check-in/check-out, and to reinitialize the processor.

8.4 Automatic Train Control

The CHHST test track system is an automatically aided, manually controlled system. The Automatic Train Control (ATC) provides the operator with speed limit information for each fixed block established by transponder distances. The speed limits and transponder distances establish the service braking pattern. A violation of these limits, enables the ATS, which puts the vehicle into emergency braking conditions. The ATC also enables levitation and landing control, departure and door control, inter-station command speed profiles, and fixed location stop control. The maximum allowance for the fixed location stopping is about 10 m when applied at less than or equal to 2.77 m/s. The accuracy of fixed location stopping is about ± 20 cm.

8.5 Evaluation and Issues

The CHSST as implemented at the test track is an automatically aided manually operated system that was incrementally developed from the Yokohama Exposition system. The Yokohama Expo system was a simple 570 m long shuttle system with fixed block speed commands, which the operator was to follow. It also had a system of transponders providing check-in/check-out of each block and an over layered overrun protection at stations. However, a simple shuttle system does not have the operational characteristics of a real urban environment that would support operation of many vehicles at 160 km/h with a minimum headway of 100 seconds and many stations. This led to the development of a continuous control system using CHSST "pattern belt."

The CHSST system that was designed in the 1970's comes out of a paradigm that 80 km/h and a manually operated signal controlled system is adequate. In the U.S. there is a need for improved operating safety and lower operating subsidies. Maglev is a technological solution to maintenance. That is, it lowers operating and maintenance costs and hence life cycle cost by eliminating friction and wear of mechanical elements in exchange for more easily replaceable electronic subsystems and components. In addition, all indications are that full automatic control can also greatly reduce the operating subsidy and therefore, needs to be examined fully. The FTA requirements call for full automatic control and operation.

The Chubu HSST engineers stated that the Tobukyu system in the Aichi Prefecture will be fully automatic. However, the automatic control system architecture was not provided in detail. Therefore, it is incumbent upon the Chubu team to furnish to the FTA Technical Team documentation on their full automatic control system architecture. Since many of the components of the full automatic control system are derived from the current computer aided manually controlled configuration, this configuration is shown in Figure 8-1. It is understood that the driver's desk will be eliminated from the architecture.

The MUSA/CHSST must evaluate the consequences of operation in poor weather environments (i.e., snow, fog, and heavy rain) that limit an operator's capability to see far enough ahead to ensure safe operation. In the U.S. environment, it may not be acceptable under these conditions to slow the system down because passengers have alternatives to public transportation, namely automobiles which are currently used far more often than public transportation systems of any kind. If Maglev systems do not demonstrate some improvement over the auto, they will not achieve the expected ridership and Maglev will not mitigate traffic congestion.

At issue is that CHSST is also developing a moving block architecture, but it too would only be used to command the operator to follow a given pattern. The vigilance of automatic systems has repeatedly demonstrated their ability to outperform the human in terms of response. In safety-critical transportation systems this is of extreme importance. The risk assessment approach developed by the FRA in a Notice of Proposed Rulemaking examines all risk elements in a system and favors the system with the least safety risk to passengers and crew. If possible, the moving block architecture should be implemented as a fully automatic control architecture. In many safety-critical systems the human operator represents a high risk element. The reliability and availability of automatic control systems have improved significantly over the last ten years and appear to offer the ability to ensure against any safety-critical failure that will result in a fatality over the life of a system. This, in conjunction with lower operating subsidies, due in large to lower operating and maintenance costs makes it essential to examine full automatic operation as a paradigm.

In addition, an ATO system with a minimum headway of 100 seconds that has a human in the control loop is prone to developing operational instabilities. As operators are directed to stay as close as possible to the service brake pattern as possible, stress levels will increase as well as errors that may result in incidents. In a shuttle system with transponders for overrun protection, stress levels and errors would not be expected to be high. But, a more complex system with operational characteristics of an urban environment would result in many instabilities, which would be manifested as delays to the system. An interim system between a simple shuttle system and a complex urban environment would be a line haul system with many stations. This would also develop delay instabilities unless station delays were controlled or adequate margin is added to ensure that sufficient time is available to damp out any possible instabilities. The consequence of adding a lot of margin to account for peak morning and afternoon delays is that the trip time would be increased. This would make the system less attractive to passengers. The impact on the station lengths of short headways and the need for several cars in a train to meet the 12,000 passenger/hour/direction was discussed previously in Chapter 4 of this report.

In the limited time available during the technology assessment at the Chubu HSST test track, there were many unresolved issues in Automatic Train Control. The differences between Automatic Train Control (ATC) and Automatic Train Protection (ATP) were not clarified. After some study of the references that this section is based on and the first hand conversations with CHSST engineers, the current system as described above represents the nature of the ATC. However, there are still a number of questions, which require further inquiry.

- Switch interlocking in the currently designed fixed block control system is accomplished in the usual manner. That is, a dispatcher provides limits of authority to the end of a block that is green with no entry into a red block. Switch interlocks are controlled by the dispatcher. The very complex mechanical switch is also interlocked with a hydraulic cylinder whose shaft must be in place to mechanically lock the switch in a given direction before three upstream blocks can be released for operation. The switch appears to function reasonably well allowing a minimum horizontal radius of 25 m to branch from one line to another. The switching time of 15 seconds does impose an operational constraint for an urban environment that needs to be examined more extensively.

- The absolute distance detection subsystem counts a set of pulses and accumulates these pulses through (*an un-described*) fail-safe process. Transponders in effect function as milestone markers for the check-in/check-out system. There is no known way to make a software processing system fail-safe. It was this very point that was responsible for the Railroad Safety Advisory Committee (RSAC) and the Notice of Proposed Rulemaking (NPRM) investigation into fail-safe processor controls. Although it was determined that true fail-safe software processors could not be designed, fault tolerant processors could be designed. Because of the increased reliability of these software processors, the safety risk associated with these processors was indeed less than the safety risk associated with so called vital electro-mechanical relays. Due to their lower cost, the software processors have distinct advantages, and are rapidly replacing vital relays that have been in operation for years. At issue is the CHSST team apparent claim to make a software process control system fail-safe. This issue should be resolved.

- The vehicle control system that receives a command signal from the ATS control, The Program Train Operation, and the driver is manually controlled by the operator. The operator responds to the service braking pattern established by the speed limits and transponder locations, and moves the throttle control lever to the appropriate speed setting. The vehicle control system in turn, generates the appropriate thrust by controlling the current from the Variable Voltage, Variable Frequency (VVVF) power supply for the linear induction motor. At the Nagoya test track the human functions as the controller and provides the feedback loop to ensure that thrust does not increase speed above its limit. In the full automatic configuration this control function must be performed automatically. The CHSST control engineers did not provide information as to how this control loop would be implemented if it were to be fully automatically controlled. That is, what type of control action would be implemented (e.g., a PID), and how should the distance and speed detection information be used? The method of providing thrust control is an important safety-critical issue that needs to be addressed, because for example, if not implemented correctly it may be possible to un-intentionally apply thrust in the forward direction when applying brakes. This is one of the key areas that should be addressed in a safety risk assessment. This thrust control function must also be examined with respect to suspension system interactions.

- Because the full automatic train control system provides the principal means of longitudinal control and safety, an independent safety risk assessment must be performed prior to the HSST system being given a waiver for operation in the U.S.. The assessment must also include all the safety-critical control functions.

9 Environmental Impact

This section addresses the impact and mitigation of noise from vehicle operations, and presence of magnetic and electric fields. Both the effects on vehicle occupants and the wayside environment are considered in the FTA requirements. The baseline used is for elevated guideway, since that is the likely choice for urban-suburban networks, and is also the configuration for which test data was taken.

9.1 Noise

9.1.1 Background

Noise from train-type systems, including Maglev, typically has three main components:

1. Structural/mechanical noise, predominant at low speeds (under 100 kph).
   There is no wheel/rail noise for Maglev, but sources do include magneto-striction (passage of strong magnets over discontinuities), mechanical brake contacts, structural and panel vibrations, and vehicle systems (heating-ventilating-air conditioning, etc.) Without the wheel/rail noise, Maglev system including the CHSST are much quieter than conventional rail in the low speed regime. This would include any re-radiation of noise from supported track components.

2. Aerodynamic noise, dominant at medium to high speeds (100-200 kph).
   This is a combination of various types of flow noise such as at corners, wakes, wind shear, boundary layer separation and reattachment, etc. This is heavily dependent on vehicle shape and air interaction with guideway or track bed structures. Both Maglev and conventional rail vehicles, if aerodynamically the same, will have similar noise in this regime.

3. Turbulent boundary layer noise at very high speeds (300 kph +)--not of interest in this discussion, but characteristic of all high speed vehicles.

Noise measurements are typically made in decibels (dB), power-related so that each 6 dB gain is a doubling of the sound level intensity. The "A-weighted" sound level (dBA) is used for environmental noise assessments because this approximates the varying frequency sensitivity of human hearing. The noise criterion in recent FRA environmental assessments used the Day-Night Sound Level (Ldn), which is based on dBA levels but taken cumulatively over 24 hr with a 10 dBA penalty weighting in night time hours.

9.1.2 FTA Requirements

Noise level requirements (□ 67dBA) are defined for measurements inside the vehicle and noise level requirements (□ 70dBA) outside the vehicle at 15.2 m (50 ft) from the centerline of the (individual) guideway.

9.1.3 CHSST Noise Measurements

Noise measurements were made for the CHSST system. The measurements taken by HSST as described in Table 3-1, Sec. 6 [1] are given as dB, but it is assumed these are dBA. For external noise, at 10m from the center of the guideway, the measured noise level at 100 kph with traction power applied was 71 dBA for a two-car consist of the 100-S vehicles. Since the sound level drops with distance, at 15 m this would equate to 68 dBA, and at 25 m it would equate to about 63 dBA, based on information developed under the National Maglev Initiative by Foster-Miller (FMI). Based on this data the CHSST has excellent low noise characteristics, and this was confirmed with an informal viewing of the passing 100-L CHSST 2-vehicle consist at the Nagoya test track by the FTA and MUSA team in March 2002. There, the traffic noise from a moderately busy secondary street nearby remained louder than the passing CHSST 100-l 2-vehicle consist at about 90 kph.

There is a slight increase in noise when the consists are lengthened with more cars. Based on FMI studies for the NMI, an increase from 2-car to 4-car consists of the same “clean” design would increase sound levels about 2 dBA, so long HSST trains would remain relatively quiet and would, within level of accuracy, meet FTA requirements at 15 m.

9.1.4 Comparison with Other Systems

Figure 9-1 below shows the noise level measured on a comparable basis for various rail and Maglev systems. This again shows how the HSST system noise is expected to be at or below comparable noise levels for comparable transportation systems.

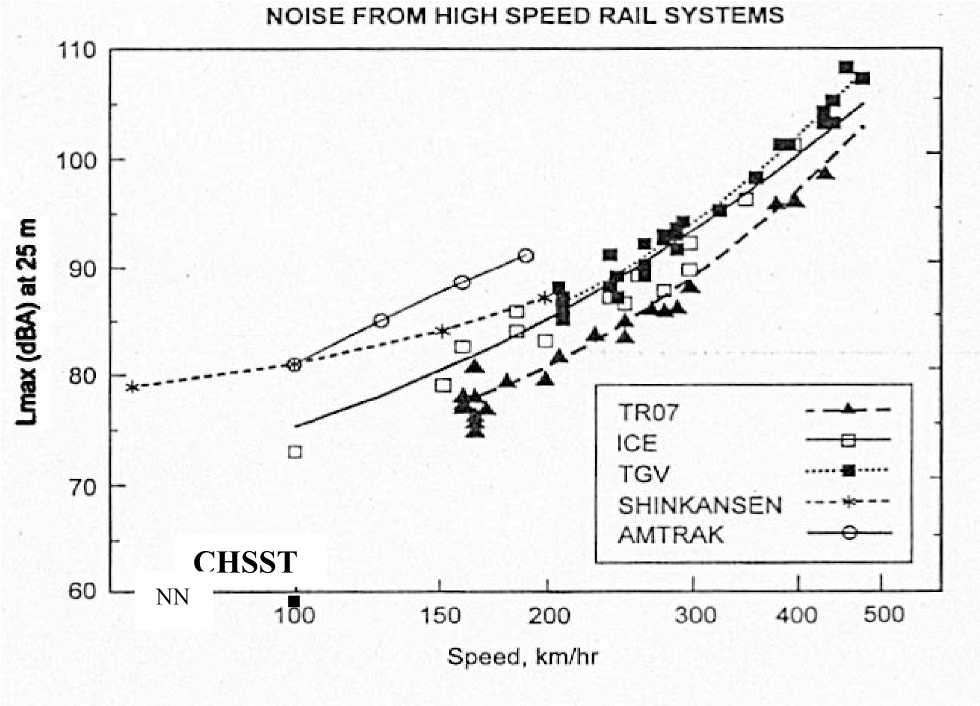


Figure 9-1. Noise from Selected Rail and Maglev Systems

9.1.5 Higher Speeds

The aerodynamic noise component rapidly increases with speed, and this would also occur for HSST. Figure 9-1 suggests that with proper attention to aerodynamics, the HSST could remain low-noise and meet FTA requirements. Past HSST data was obtained with the relatively blunt-nosed 100-S vehicles. However, the 100-L vehicle is more streamlined, affecting the informal witnessing that occurred in Nagoya in March 2002. The projected body style for the Tobukyu Line vehicles is more blunt than the 100-L, so if higher speeds such as 130 kph and certainly 160 kph are required, a more aerodynamic and streamlined body with small gaps and other projections should be considered.

It would also be appropriate to conduct additional measurements at 15.2m and 25m laterally from the guideway center to confirm the expected results, using the present test vehicles. Also obtaining data from the Tobukyu Line when it is operational would be desirable, since the present test track cannot be used for speeds over 100 kph.

9.2 Electric Fields

The electrical field limits are based on the ACGIH 1999 standards. The AC electric field allowable for public exposure is 1 kV/m for medical electronic wearers and 5 kV/m for the general public. The AC electric field intensity for personnel working on the equipment for eight hours per day is 25V/m for frequencies up to 100Hz and $2.5\text{x}10^6/\text{f}$ V/m from 100Hz to 4kHz (where f = frequency in Hz). This overlaps with a restriction for higher sub-radio frequencies (300 Hz to 30 kHz), where the allowable AC electric field is $2.5\text{x}10^6$ kV/m for eight hour/day occupational exposure.

There is only one test data point of the electric field available for the CHSST vehicle. It was done at the trolley rail and the data is not presented in [1]. There is a comment that the specification would be met at a distance of 10m from the trolley. Therefore, additional testing or test data is required to verify that the specifications can be met.

9.3 Magnetic Fields

These magnetic field limits are also based on the ACGIH 1999 standards. The static (DC) magnet field continuously allowable is 5 Gauss (G), which is the limit for medical electronic device wearers. This standard was established based on persons with cardiac pacemakers and other implanted electronic devices, and is about 10x the earth's magnetic field. The allowable AC time-varying magnetic field must be less than 1 Gauss at frequencies from 1Hz to 300Hz. The static DC magnetic field is limited to 1 Gauss for workers with cardiac pacemakers who also work on the equipment for eight hours/day. This AC magnetic field may increase to 2 Gauss for sub-radio frequencies (300Hz to 30kHz).

The CHSST magnetic field strength was measured outside the vehicle at the platform. The measured value was 5.3G, which would equate to about 53 mG at 10 meters from the track.

Figure 9-2 below indicates the magnetic field strength for the TR-07 Maglev system, inner-city rail and normal urban transit systems. At ten meters distance, the measurements for the DC field ranged from 40 mG to 60 mG. These measurements are in the same range as the CHSST measurements, and so the CHSST vehicle presents no different behavior than traditional electric transit vehicles. The CHSST specification is 1 mG @ 25 m. This is in the same range as today's Inter-City Rail Specification.

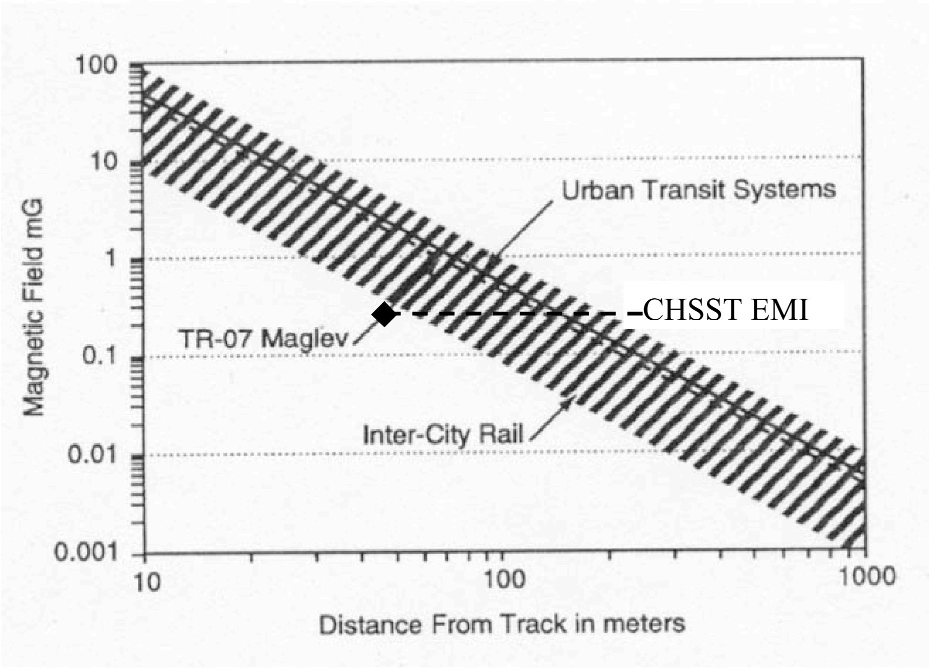


Figure 9-2. External Magnetic Field Strength for Selected Rail and Maglev Vehicles

The CHSST magnetic field strength was also measured inside the vehicle. The measured value was 18.5 G (DC magnetic field) at the floor, and was reduced to less than 5 G at seat level (50cm above the floor). These measurements were made under full acceleration conditions, approximately 1.1 m/sec^2. When static levitation tests were made, the value was 2.8 G at the floor, significantly lower than when the vehicle was accelerating at its maximum rate.

This is an area for additional performance tests to determine the field strength when higher acceleration rates are achieved, since that is the condition for greatest potential magnetic exposure.

9.4 U.S. Mandatory and FTA System Requirements

These have been described in the individual sections above. The FTA limits for noise and electric and magnetic field exposure have been based on the referenced U.S. industry sources, and represent conservative guidelines for long-term exposure for both passengers and workers. In some cases differences between the two levels are noted.

9.5 Evaluation and Issues

The CHSST system generally meets the FTA guidelines for noise and electric and magnetic field exposure, as discussed in detail above. Also, they are comparable to other conventional electric rail system vehicles now in service, within a reasonable range of accuracy. The following areas, however, need further clarification or testing:

- Additional testing or test data would be required for certain areas, especially if the performance (speed, acceleration) were increased to meet other FTA requirements. This includes overall external noise at speeds greater than 100 kph, and with new body shapes. Also, magnetic field strength needs to be confirmed with accelerations raised to the FTA requirement of 1.6 from the present 1.1 m/sec^2.

- Electromagnetic interference (EMI) measurements should be made inside the CHSST vehicle since the initial measurements are greater than the specification.

- Electric field measurements must be repeated for the sub radio frequency range since these measurements exceeded the specification.

10 Performance and Safety Tests

Prior to 1993, the HSST engineers performed a large number of tests as reported in [1]. In addition to the performance and safety tests on a “finished product” which are of specific interest here, the list presented in this reference also contains a number of developmental tests. Although testing continued after 1993, a comprehensive list of these tests was not available to the authors. The Aichi Prefecture apparently considered the tests prior to 1993 adequate to conclude that the HSST system is a safe and economic Maglev deployable for urban transportation. The pre-1993 tests as reported in [4] are the following:

1. Vehicle. A total of 44 items were tested. These tests were broken into three subgroups: levitation/guidance, propulsion/braking, and vehicle/onboard equipment. The tests were conducted under different conditions: (dry, rainy and snowy weather; no load and full load; and various vehicle speeds).

Levitation and guidance were done with emphasis on the performance at 100 kph. Anomaly tests, such as the module drop test and skid slide test were included in this series of 15 tests. In the opinion of the Japanese engineers, only one item, landing skid durability, needed improvement prior to production.

Propulsion and braking tests were focused on the deceleration of the vehicle from 100 kph. Special emphasis was placed on brake performance in the electro-hydraulic braking mode (i.e., the combination of linear motor and hydraulic mechanical brakes) and emergency measures. 17 test items were ranked OK, and only one item, electrical power requirement, needed additional design research.

Eleven tests of the car structure and onboard equipment were conducted. Based on the Japanese engineers’ assessments, all 11 tests were completed with no design improvements required. These tests included a current collection test conducted at 110 kph.

2. Guideway. Three groups of items were tested: track structure, switching devices, and dynamic load conditions on the structure.

Eight tests to establish the drop load of the vehicle and track load conditions while the vehicle was levitated were successfully completed. However, during the tests, all of the values were below the tentative values established for the construction of the test track. Various types of guideway configurations (steel beam, pre-stressed concrete beam, steel beam plus steel sleepers, and pre-stressed beam plus steel sleepers) were measured. Track deflection and accuracy were also measured under multiple conditions. The ninth test found that the steel sleeper style needed improvement prior to production. A 127 Hz rail vibration was observed at some guideway positions.

Four switching tests were completed which confirmed switching accuracy. An endurance of 90,000 cycles completed successfully. No redesign was necessary prior to production.

3. *Power Supply/Signal Security Systems.* The systems were basically the same as used in today's railroads. Fourteen items were tested, all of which met the design criteria. The complete tests included: higher harmonic measurement, ground fault detection, and noise level measurement for the signal system.

4. *Safety in an Emergency.* This was a test to verify that the emergency skid operation worked properly for a car that lost levitation on a 7 percent grade.

5. *Overall Test/Operation Test.* Noise and vibration were measured. The magnetic field strength inside and outside the car were also measured. All nine items tested met the Japanese design criteria.

10.1 Additional Performance Tests

The following additional tests on the CHSST vehicle are recommended by the FTA team.

- Acceleration, Deceleration, and Speed
  These performance tests indicate certain limitations of the CHSST system. Clearly, the acceleration, deceleration and maximum speed are limited in view of the FTA requirements. CHSST acceleration is limited to an initial rate of 4 kph/sec (2.48 mph/sec) that drops to 2.87 kph/sec (1.78 mph/sec) at 85km (~53mph). CHSST deceleration is limited to 4.83 kph/sec (3 mph/sec). Note that today's new steel wheel-steel rail transit cars have top speeds of 160 kph (~100mph), accelerations of 4.84 kph/sec (3 mph/sec) and a decelerations of 8 kph/sec (~5 mph/sec). Maglev, which is independent of adhesion limits, should have superior performance. However, any changes to CHSST parameters require a system redesign or re-evaluation. This means that most of the performance tests would need to be repeated after the system was redesigned or upgraded. The present CHSST performance limitations may lead to capacity restrictions or to decreased passenger satisfaction if the system is used in the U.S. environment.

- Power Consumption
  The power requirements for levitation and propulsion favored the use of the two-rail 1500 volt DC supply. This needs to be evaluated during a variety of weather conditions. The electrical power consumption for levitation was measured at 13.45kw at 100 kph per vehicle. This is 50% more than the power required for levitation at a standstill. More testing is required to determine the fundamental reasons for this change.

- Vehicle Endurance Test
  Vehicle endurance tests have been performed for only a relatively short total distance (41 km). This test was performed after 1993 and test results are reported in [4]. This test should be continued for at least another 150 km, at full speed and fully loaded.

- Rail-Sleeper Endurance Test
  The steel rail on the guideway transmits the vehicle load by means of a cantilever action onto the sleeper. The rail is bolted to the sleepers. Each time a car passes over

a sleeper, cyclic stresses are created which can lead to fatigue cracks in the cantilevered rail section, bolts, and sleeper holes. The endurance test on the rail/sleeper attachment should be simulated in the laboratory. The number of cycles for any fatigue failure and loosened bolts must be evaluated for correlation to the expected service life. This will determine the required frequency of inspection.

- Vehicle Dynamic Response and Ride Quality Test
  Vehicle dynamic response and ride quality measurements must be performed at full speed with all guideway irregularities set in the track and under full load of the vehicle. Much of the data shown by the HSST engineers seem to be generated from theoretical simulations. The testing provides confidence in the theoretical data and may reveal problems, if any, of a vehicle negotiating simultaneously existing irregularities.

10.2 Additional Safety Tests

The FTA team recommends the following additional test for assurance of passenger safety.

- Passenger Interior Injury Assessment
  When the emergency brakes are applied, the sitting and standing passengers in the car may be displaced and injured due to their impact on rigid interior components. Substituting dummies for passengers, tests should be performed to assess the safety of the passengers under emergency braking conditions.

- Vertical Control System Test
  Since the Electromagnetic Suspension system is unstable, without active vertical control, tests should be done to determine possible loss of vertical control under power outages, electronic component failure, sensor failure, etc.

- Crashworthiness Tests
  Vehicle structural crashworthiness tests simulating collisions with large sized objects (such as large tree branches, but still to be determined) are required to assure structural integrity and the safety of passengers in the event of a crash.

- Egress Test
  Safe egress of passengers, including those defined under the ADA, must be demonstrated in a test simulation.

- Flammability Test
  Tests are required to demonstrate countermeasures and passenger safety under fire and smoke conditions.

- Automated Train Operation
  A test demonstration of the automated train operation under close headways is required, as discussed in Chapter 8.

11 System Costs

11.1 Introduction

Cost information for the CHSST system has been assembled from several sources. The primary sources were the local and central Japanese government bureaus responsible for managing the financing, construction and operation of the Tobukyu Aichi Expo line. Construction of this system will start in 2003, with completion in 2005. This is the first and only revenue application of CHSST to date, so the extensive planning and study efforts conducted in Japan starting over ten years ago provided this cost data.

The Japanese projected cost information for this line in turn originated from both the 1993 comprehensive planning document [1] used for approval of the system, and information provided by the Aichi Prefecture officials to the FTA/MUSA visit to Japan in March 2002. Both the national Ministry of Land, Infrastructure and Transportation (MLIT) and Aichi Prefecture provided planning and financing services. Program and operations management was provided by the Prefecture supported by a network of contractors and subcontractors.

The cost breakdowns for both the initial construction and for operating costs were detailed only down to the general category level: i.e., capital costs for track components, support structures (infrastructure), substations, signal communication system, passenger stations, etc. and operating costs for cost of electrical power for vehicles, station upkeep, guideway maintenance, etc.

The actual costs assembled in 1993 were for a “baseline” system that was not exactly the same as the Tobukyu Line, which had not been laid out at that time. The ’93 baseline system was a 10 km, 11 station layout while the Tobykyu Line is a 9.2 km, 9 station layout with some infrastructure features tailored for the 2005 Aichi Expo. The ’93 study was aimed at comparing the relative economic and social merit of the CHSST system vs. a typical Japanese monorail system and a “new” medium capacity rail-like system. However the proportioning for the various capital and operating cost categories was valuable and is used in this discussion.

These cost proportions as given in the 1993 analysis vs. the later 2002 visit were then compared. Breakdowns given in 1993 were adjusted based on the later information. Also, the industrial inflation from 1993-2002 was looked at for both the U.S. and Japan, including the differing dollar-yen exchange rate. While a detailed economic analysis for a U.S. application is beyond the scope of this report, an attempt was made to identify any likely and obvious U.S.-to-Japan differences and then project a range of costs for a U.S. application.

11.2 System Level Construction Cost Breakdown

Presently, construction costs for the new Tobukyu Line are estimated at about 110 billion ¥ (880 million $ at the current 128 ¥ /$) for guideway, stations, power facilities, etc. The tunnel section at 26.6 B¥/km will be 3x the unit cost of the elevated section at 9.1 B¥/km. 40% of the cost will be borne by a combination of private and public companies, and will be recouped in about 20 years. 60 percent of the cost will be provided by the local, prefectural and national government. The 40 percent portion represents the "Maglev" part (active guideway portion, cars, signals, etc.), and the 60 percent represents the infrastructure (guideway supporting structures, site work, tunnels, etc.).

Using the elevated configuration as a common reference, the total cost of the CHSST Tobukyu Line is approximately $115 M/mile based on a straight translation of the current estimate of 9.1 B¥/km to U.S.$ at a 2002 exchange rate of 128 ¥ /$. There are several factors which should be considered in understanding this cost.

A percentage cost breakdown of the CHSST system costs was computed from past Japanese data used for study and approval of the Aichi Expo line (Table 4-6, Ref 1). This study estimated the costs/km for the "baseline system" to be 5.83 B¥/km in the 1992 time frame.

Table 11-1. Percentage of CHSST Construction and Deployment Costs*

Guideway Structures & Track		37%
Power Substations & Distribution		12%
Signal & Communications		9%
Stations & Buildings		19%
Infrastructure	12%	
Fitout & Equipment	5%	
Other Buildings	2%	
Vehicles		14%
Yards		4%
Land (Substations/Yards)		5%

* Based on 1993 Economic Analysis of "Baseline" System (10 km, 11 stations, not "Expo" System)

Table 11-1 can be used as a general guideline, or starting point for proportional costs of a CHSST two-way urban-suburban system, excluding infrastructure impacts for the route. This reflects the Japanese environment, and U.S. vs. Japanese issues will be addressed in a later part of this section.

There has been more than a 50 percent increase in the overall estimated cost/km of the CHSST elevated configuration from 1992 to 2002: from 5.83 to 9.1 B¥/km. To understand this, we considered several possible factors.

The relative inflation rate in Japan was very low (under 2 percent) over that time, although the inflation rate in the U.S. was approximately 22 percent. Therefore other factors should account for the increase of the costs in Japan. These could include:

- Current costs are based on actual "hard" quotes with specific bids based on detailed designs, as opposed to preliminary estimates;
- The Tobukyu Line may include "Expo" features not directly related to the Maglev system, such as more elaborate or larger stations, parking and roads;
- Negotiation of urban areas such as curves requiring building removal or eminent domain proceedings;
- Design changes made over the interim based on technical needs, more stringent government regulation, safety-related or reliability-related redundancy, etc.

The following subsections provide more detailed breakdowns of the major cost areas, where available from CHSST and MUSA. The guideway system, for example, is the single largest capital cost contributor, and so was subjected to a more detailed breakdown. Also, supporting calculations and data available to FMI were used to assist the discussion.

Cost breakdowns for other elements such as the vehicles, power system and train control/protection systems however, were not provided, and so these subsections reflect only their percentages of overall system costs as shown in Table 11-1 above. For this purpose, an estimated cost for an "all-elevated" version of the Tobukyu Line was prepared, based on reducing the cost of the 1.8 km tunnel portion by a factor of 3 (the tunnel section was 20 percent of the total 9.2 km length). Using current exchange rates, this "all-elevated" total cost was approximately 760 M$ (vs. the original 880 M$ cost with the tunnel section included at its full cost). These were based on costs cited earlier in this subsection.

11.3 Guideway Cost Breakdown

Independent cost estimates at Foster-Miller showed a basic cost of approximately 35-50 M$/mile for a two-way CHSST "basic" elevated guideway, not including vehicles, stations, substations, support facilities, signal/communication systems, yards, land, etc. This report considers the complete guideway structure, "Maglev" components and power rails for the normal elevated single-pylon configuration . Standard 20-24m pre-stressed concrete guideway beams plus sleepers were assumed, plus good soil conditions not requiring deep pilings or other extraordinary measures.

There is good agreement, for example, between the FMI basic guideway cost estimate of 40 M$/mile for the CHSST configuration and the Japanese-quoted costs, using the percentage in Table 11-1 above: 37% x 115 M$/mile = 42.5 M$/mile for the basic elevated guideway and track system.

These proportions, therefore, can be valuable in understanding how potential costs for a U.S. urban-suburban system might be allocated, assuming a straightforward two-way linear layout with station facilities at approximately 1 km (0.6-0.7 mile) intervals, and connecting to other transportation facilities at each end.

The basic elevated CHSST guideway can be proportioned as shown in Table 11-2 (including manufacturing, transport, and complete installation). This uses Ref.1 (1993) CHSST data for proportioning the guideway structure vs. the rails, sleepers and reaction rail which comprise the "Maglev" components. Then the guideway structure was subdivided based on proportions used in the 1992 FMI U.S. Maglev study for the NMI.

Table 11-2. Possible Breakdown of "Basic" Guideway Costs

Pre-stressed Concrete Beams & Attachments	62% of total basic guideway
Concrete Pylons, Footings	19%
Other (walkways, ladders, etc.)	5%
Track Rails, Sleepers & Attachments	13%
Reaction Plates (for LIM)	1%

The information above can therefore serve as an initial guide for cost breakdown of the HSST guideway system. If new U.S. applications require more or less expenditure in a particular category to suit specific conditions, the proportional effects on overall costs can be estimated. This, for example, could include local foundation/subsurface conditions, special station requirements or unusual crossing spans.

11.4 Vehicle Cost Breakdown

A breakdown of the vehicle costs was not provided by CHSST or the constructor for the Tobukyu Line (Nippon Sharyo). From the overall system breakdown based on [1] (Table 11-1 above), about 14 percent of the system cost represented vehicles. (Note that [1] was for a "baseline" system, not the Tobukyu Line.) This would amount to about 105-110 M$ for vehicles based on the estimated "all-elevated" Tobukyu Line cost of 760 M$. If ten 3-car consists (including spares) are to be purchased, this would result in a unit cost of 3-4 M$/vehicle; also these are the "long" 90-95 passenger vehicles similar to the 100-L. (Again, the capacity is based on the 3.3 sq ft/standee appropriate for the US.) Both the number of vehicles and their actual cost would need to be provided by MUSA for a proper comparison to FTA requirements. However, that target of 1.5M$/vehicle could be exceeded based on the assumption of 30 vehicles included in that system.

11.5 Power Supply Cost Breakdown

A breakdown of the power system costs was not provided by CHSST. From the overall system breakdown based on [1] (Table 11-1 above), about 12 percent of the system cost represented power supply and distribution. (Note that Ref. 1 was for a "baseline" system, not the Tobukyu Line.) This would amount to 90-95 M$ for the power/distribution system based on the estimated "all-elevated" Tobukyu Line cost. This category would include the utility tie-ins, power conversion (1500 VDC in this case), regulation, substations, distribution, etc. It is assumed that line sections would be fed in such a way that a single line break would not stop the system, but that alternative feed routes would be available, similar to conventional electric rail systems. Their current costs would need to be provided by MUSA for a proper understanding of their contribution to the system.

11.6 Automatic Train Operation/Protection, Signal and Communication Cost Breakdown

A breakdown of the ATO, Train Protection, Signal and Communication system costs was not provided by CHSST. From the overall system breakdown based on Ref. 1 (Table 11-1 above), about 9 percent of the system cost represented the train control/protection, signal and communication systems. This would amount to 65-70 M$ for those systems, based on the estimated "all-elevated" Tobukyu Line cost. Their current costs would need to be provided by MUSA for a proper understanding of their contribution to the system.

11.7 Station Costs

A breakdown of the station costs was not provided by CHSST. From the overall system breakdown based on Ref. 1 (Table 11-1 above), about 17 percent of the system cost represented stations (with fitout). This was for a "baseline" system with 11 stations, but using the estimated "all-elevated" Tobukyu Line cost, this would work out to about 130M$ for stations, or 10-12 M$ each. Their current costs would need to be provided by MUSA for a proper understanding of their contribution to the system, but it appears station costs could well exceed the FTA requirement of 2 M$/station. However, it is not known what constituents are assumed to be present in either number (parking facilities, non-standard station features, access roads, etc.), so this awaits further clarification by MUSA.

11.8 Cost Comparison with Light Rail

The construction cost of the CHSST maglev, in its proposed revenue form, can be compared with other urban-suburban transportation systems such as a light rail line. Such a comparison must be obtained by comparing the capital costs of systems which provide the same level of ultimate service; i.e. the performance and physical differences should be accounted for in arriving at what are the truly "comparable" systems to service a given area. Such aspects would include differences in acceleration/braking, maximum speed, grade-climbing ability, and curving limitations to cite a few examples. Also, market demand differences should be accounted for in load factors, daily schedules of operation, train capacities, etc.

11.8.1 Comparison For Japanese Systems

Such a comparison was performed in the 1992 time frame as part of the HSST system Economic Feasibility Study [1]. For the HSST system, the "baseline" 10 km, 11-station layout was used, not the Tobukyu Line which had not yet been laid out. The comparison was made with two alternatives: a monorail system and a "new transportation system", similar to elevated light rail adapted to the need for elevated layout in the urban-suburban street environment. Each of these three alternatives was first specified in terms of their performance and capacity capability, plus adjusted for market demand/forecasting per the discussion above in an effort to provide a valid basis.

To provide data for the monorail and "new" light rail systems, six examples of each that already existed in Japan were used, and then a representative system was developed for use in the comparison. The "new transportation" or light rail alternative had, for example, a lower top speed (60 kph vs. 100 kph), slightly lower acceleration/braking rates, and slightly smaller capacity in the 4-car train (used for both). The system data are available in detail in Tables 4-1, 2 and 3 [1].

When applied to the same "baseline" layout, both the new light rail system and a monorail system came out to a slightly higher cost than the HSST system. The detailed results of the cost comparison is available in Table 4-6 [1], although there is a inconsistency between the written text and the table on the identification of these two alternatives. In any case, recall that in 1992, the projected HSST system cost was 5.83 B¥/km, while (according to Table 4-6 [1]) the "new" light rail alternative was 6.13 B¥/km, about 5 percent higher. This is certainly within the accuracy of the many assumptions required for such a comparison, so the conclusion is that for Japanese applications, and with the assumptions used for the 1992 study, that the costs are comparable.

Also, it was remarked by Aichi Prefecture officials at the March 2002 meeting in Japan with the FRA/MUSA team that the light rail alternative was thought to be about 15 percent greater cost. This is a greater difference, possibly reflecting later interpretation of such a comparison.

11.8.2 Need for Comparison For US Conditions

For U.S. conditions, MUSA should perform a similar level of comparison with the light rail alternative covering the factors discussed above. It is likely that the specifics of the system layout used as the basis of that comparison will affect the outcome, since the comparison made in Ref. 1 showed the costs to be relatively close. Therefore, attention should be paid to the relative sensitivities of all the major assumptions such as performance, capacity, etc. For example, it is reported that some newer light rail systems may have better performance than the older ones used in the 1992 Japanese comparison. Likewise, a system meeting the current FTA requirements also has a higher level of performance than the existing implementation of the CHSST in Japan.

11.9 System Level Operating Cost Breakdown

11.9.1 Revenue and Operating Costs

Using the Tobukyu Line figures provided by Aichi officials, revenue is projected to be about 2.8 B¥/yr—90 percent of which is operating cost and 10 percent used to retire the 4 investment portion above. The 2.5. B¥/yr (19.5 M$/yr) operating cost is divided as shown in Table 11-3.

Table 11-3. Projected Tobukyu Line Revenue Breakdown

Personnel	0.6 B¥/yr	24% of total
Running, including power	0.7 B¥/yr	28%
Taxes	0.3 B¥/yr	12%
Debt Service	0.9 B¥/yr	36%
Total	**2.5 B¥/yr**	

If revenue is 2.8 B¥/yr for 31,000 passengers/day averaged year-round, and the break-even point is 26,000 passengers/day, then the 0.3 B¥/yr can be used to retire the 40 percent "Maglev Portion" cost.

A further breakdown of the "running" costs of 0.7 B¥/yr is shown in Table 11-4.

Table 11-4. Running Cost Breakdown for Tobukyu Line

Guideway maintenance	40 M¥/yr	6% of total
Electrical except Power	150 M¥/yr	22%
Vehicles	110 M¥/yr	16.5%
Traffic/Stations	110 M¥/yr	16.5%
Power Costs	130 M¥/yr	19.5%
Miscellaneous	130 M¥/yr	19.5%
Total	**670 M¥/yr**	

These all can be useful benchmarks for proportioning costs in similar systems, allowing for the differences in the specific layout, U.S. regulations and design features, operating structure, etc.

Labor costs for operations in the U.S. may be an issue when using these costs based on Japanese operating practices. For example, the projected Tobukyu labor costs are a quarter of the total operating costs, which could be a low proportion for a U.S. system. Also, the Japanese environment may tolerate relatively higher fares than the U.S., in which substantial subsidies are demanded for regional and urban systems. The projected regional Tobukyu Line revenue of 22 M¥/yr carrying 11.2 M passengers means an average fare of $2 for a mix of trips on a 9-station 5.7 mile system, which is short by U.S. standards.

11.10 Evaluation and Comparison with FTA Cost Goals

11.10.1 Capital and Construction Costs

The projected capital costs for the elevated portion of the CHSST Tobukyu Line including stations, at 115 M$/mile is 43% higher than the FTA goal of 80 M$/mile for the complete two-way system. Higher specific costs in Japan could account for a high overall amount relative to a U.S. deployment, including:

- Use of actual “hard” quotes as opposed to preliminary estimates
- Inclusion of “Expo” features not directly related to the Maglev system
- Negotiation of specific urban areas, and
- Design changes made during the interim

Thus, CHSST needs to point out these or any other special considerations that may have contributed to assist in obtaining a more representative U.S. “baseline” cost figure. However, the overall observation is that this is not an inexpensive system even by Maglev standards, as shown by comparison to the current Transrapid deployment in China. Note that the in-tunnel portion of the Tobukyu Line (at 3x the unit cost) was not included in this comparison.

The system breakdown analysis by FMI (Table 11-1) showed that proportioning of the major cost elements based on the CHSST 1993 baseline system, was reasonable based on other Maglev system studies. CHSST should consider addressing any special costs in the Tobukyu Line information above. The “basic” two-way elevated guideway, one of the most important system elements, came to a cost of approximately $37-42 M/mile, substantially exceeding the FTA goal of $22 M/mile. Again, this is higher than anticipated for a simple guideway with no active electrical elements in the guideway.

The further cost breakdown of the “basic” guideway (the structure and rail system, excluding the signal system, power distribution, associated infrastructure costs, etc.) was shown in Section 11.3. 60-65% of this comprised the beams, and about 20% more comprised the pylons/footings, based on earlier FMI studies of Maglev costs for the U.S. NMI program. This would suggest that efforts to highly engineer the design and manufacture of the basic beam, by optimizing the reinforcement, material properties and manufacturing plant, could reduce costs. However, the cost of the pylons/footings did not consider the more expensive "all-piles" approach taken in Japan for conservatism in their design and implementation for the Oe test track, nor for any (unidentified) areas of the Tobukyu Line.

The costs for the other system elements: vehicles, power supply/distribution and the train control/protection, signal and communication, and stations were not broken down by CHSST. Only a rough estimate for their cost was made, based on the proportional costs used in the 1993 study by Aichi Prefecture (Ref. 1), and an adjusted total cost for a Tobukyu Line assuming "all-elevated" construction. All these estimated costs exceeded FTA targets, but they could be revised if actual cost data were furnished by CHSST or MUSA.

11.10.2 Operating Costs

The projections for the planned Tobukyu Line have been detailed above, showing an average fare of $2 for a mix of trips over the 9-station, 9-km system. The mix and average length of trips is not known. To compare with the FTA operating cost goal of $15/vehicle-mile ($9/vehicle-km), the average car loading (load factor) and average trip length should be provided by MUSA. Then the effect of US conditions vs. the Japanese environment must be factored in, as needed. In general, a $2 fare for predominantly short trips might be considered excessive in the US, but this would depend on the demand and any subsidy available for a specific area.

12 Conclusions and Recommendations

The FTA team evaluated the CHSST system based on the trip to Japan during March 2002, the three MUSA reports and the 1993 Aichi Prefecture report. The team arrived at the following conclusions and tentative recommendations for consideration by the FTA and MUSA. The FTA requirements that have been used as a benchmark are for a generic system and specific to any alignment. The requirements of specific alignments may be less stringent than projected in the generic system.

12.1 Conclusions

12.1.1 System Level

The HSST is a mature Maglev system for urban applications developed in Japan over the last 25 years. It has not been introduced on a commercial revenue line anywhere yet. Under financial support from the local and central governments in Japan,the CHSST Maglev is expected to be built in the eastern suburb of Nagoya over a 9.2 km distance. Construction on the project is anticipated to start in 2003 to be completed in 2005, and will provide revenue service for 31,000 passengers per day. A three car train with a capacity of 400 passengers is planned for the daily operations with a head way of 6 minutes catering for 4,000 passengers per hour per direction. According to the 1993 Aichi Prefecture study, the HSST Maglev can economically compete with Light Rail and provide additional benefits such as quiet operation, reduced pollution, trip time savings, and the ability to negotiate 7 percent gradients.

The FTA requirement is 12,000 passengers/hour in each direction which can be met by the CHSST system only by increasing the number of cars in the train and reducing the headway significantly. For this capacity, a three car train will have to operate with 75 second headway. This level of headway is stringent, and should be assessed for safety and feasibility for the HSST system. An eight car consist of 100- S vehicles requires 2 minute headway to meet the capacity requirement. Car capacities are figured on accepted passenger densities for U.S. urban rail systems. The consist /station length will be about 68m(225 ft) for this case. Hence, the increased number of cars increases the train length, which in turn requires long stations. Even if it is possible to locate such large stations in an urban environment, every kilometer or two along the guideway, it will be difficult to gain public acceptance due to aesthetic considerations.

The HSST in its current state of development does not satisfy some of the U.S. mandatory and FTA requirements, which are summarized later in this section. Despite this, the system has a potential for application in the U.S. and is among a very few commercially feasible systems to date for Urban Maglev. If deployed in the U.S., it would provide significant information, awareness and exposure of this urban maglev technology to the U.S. public, transportation planners, and investment sources such as the state and federal governments, private companies, and financial institutions. Such a technology can revolutionize the transportation industry. At the moment it is unknown whether the CHSST Maglev can compete with a conventional system on a cost basis because of the lack of real data.

The HSST technology was conceptualized in the 1970's with a Linear Induction Motor on a test vehicle. Alternate concepts by others have included the application of Linear Synchronous Motors (LSM) for propulsion and braking. The application of LSM technology would result in a lighter vehicle, but makes the guideway relatively expensive. However, the LSM concepts have not yet resulted in any full scale operating vehicle for urban transportation. Hence it is not known how CHSST technology compares in practice with other emerging Maglev technologies. Presumably the simpler guideway of the HSST system could reduce capital costs, but this needs to be proved for the CHSST Maglev system.

12.1.2 System Costs

The projected capital cost for the two-way elevated portion (i.e., excluding tunnel but including stations) of the CHSST Tobukyu line is $110-115 million/mile, over 40% higher than the FTA goal of $80 million/mile. The system costs include the basic two-way guideway, vehicles, electrical systems, stations, signal and communications, etc. The "basic" two-way CHSST elevated guideway cost is in the range of $37-42 million/mile, which is almost double the FTA desired value of $22 million/mile.

The FTA requirement may be optimistic and difficult to achieve. Nevertheless, the cost of the CHSST system should be further evaluated under the best possible normalization for U.S. conditions. The guideway structure, including foundation supports should be optimized for strength and cost using a demonstrable rational procedure. Cost comparisons with elevated light rail and monorail, if appropriate, should be made when considering the CHSST system deployment in the U.S.

12.1.3 Guideway Structure

- The selected structural safety and ultimate load factors seem to be reasonable.

- The life of the guideway and its components must be evaluated to satisfy the FTA requirements. For the permanent infrastructure (guideway, beams, supports) the goal is 75 years. The rail and attachment goal is not specified in the FTA requirement, but a life of 30 years is reasonable. The rail and sleeper life also should be evaluated.

- The foundation and pylon at the test site represent potential over designs for general applications, and tradeoffs are required to replace them with spread footings of mini piles where allowed by subsurface conditions.

- Thermal distortions should be thoroughly studied for special guideway sections using steel, and in the design of direct fixation techniques contemplated in future applications to reduce the guideway cost. The conditions at Nagoya do not represent the extreme conditions encountered in the U.S.

- In view of stringent guideway tolerances, a method of monitoring by specially designed inspection vehicles and the inspection frequency should be addressed as a part of the guideway maintenance plan and safety assurance.

- The switch existing on the Nagoya test track appears bulky and expensive for revenue service applications. Alternate switch designs for space efficiency and reduced costs should be developed. Possibly different designs for both yard and en route applications are needed.

12.1.4 Vehicle Structure

- The HSST vehicle operational speed is currently limited to about 100 kph. It cannot satisfy the FTA maximum speed requirement of 160 kph.. The CHSST technical staff stated that the vehicle can be operated at 130 kph without major redesign. Our calculations indicate that in the scenarios where the station spacing is not large, this reduced speed may not impact trip time significantly and the 130 kph vehicle may be acceptable on some routes in the United States. For long station spacing, the trip time will increase and the 160 kph speed for the vehicle will be needed. Since a major redesign will be required to upgrade the current HSST vehicle to this higher speed, the current CHSST vehicle upgraded to130 kph would appear to be more applicable for potential applications in the U.S. at locations with closer station spacing.

- The 100-L vehicle cannot satisfy the FTA requirement of the 18.3 m (60 ft) radius curve negotiation. The 100-S vehicle comes close to the requirement with a minimum radius capability of 25m (83 ft). MUSA must evaluate the applicability of 100-L vehicles in the U.S. scenarios by studying potential Maglev routes in urban areas.

- The HSST vehicle has a life of 20 years according to MUSA report. The FTA requirement is 30 years. The HSST vehicle life must be analyzed and some redesign may be required to increase its life to the FTA minimum limit.

- There is a US mandatory requirement for passenger egress in the event of smoke, fire and other hazards. This must be adequately addressed, because the vehicle does not have windows or hatches for passengers to open and escape, or for rescue access.

- The level of crashworthiness of the vehicle is unknown. The vehicle nose must be analyzed and redesigned where necessary to assure some level of passenger protection from impacts at reasonable speed.

- The vehicle interior layout should be modified to satisfy the mandatory ADA requirement, which can impact passenger capacity and interior seat layout. Additionally, the passenger car capacity for U.S. operations needs to be based on an adequate floor area of 0.3 m^2 (3.3 ft^2) per standee as reflected in some MUSA data. The smaller area of 0.14 m^2/standee, while acceptable in Japan, is insufficient for U.S. application.

- The vehicle weight should be reduced to enable increased propulsion power and to potentially operate the vehicle at a higher levitation gap. Reduced vehicle weight can reduce trip time, increase grade climbing capability and lessen restrictions on guideway construction and maintenance tolerances.

12.1.5 Vehicle Levitation

- The HSST technology permits the vehicle to remain levitated at stations at zero speed. This is an advantage over Electrodynamic Systems which generate repulsive forces and need some minimum speed for levitation.
- The physical levitation gap of the HSST vehicle is on the order of 6 millimeters, which is quite small in view of the guideway tolerances, which must be maintained and the transient loads that must be sustained.
- The robustness of the lateral guidance and control should be evaluated further with regard to effects from wind gusts and aerodynamic forces from passing trains.
- The reported delevitation of modules during the endurance testing should be properly explained and its impact, if any, on the design criteria and reliability of the levitation system should be clarified.

12.1.6 Vehicle Propulsion and Braking

- The CHSST vehicles do not have sufficient thrust capacity to climb the maximum grades without degradation in speed. On a 7% grade with a headwind of 25 m/sec (55 mph), the achievable steady state speed is 53 kph, which does not satisfy the FTA requirement. To improve the thrust performance, the LIM will need to be redesigned as discussed in Chapter 6, and if possible, the car weight reduced as discussed in Chapter 4.
- An upgrade in the braking performance of the CHSST vehicle will be needed to satisfy the FTA requirement. The requirement arises because of close head way operations to meet the throughput requirement along with the need for frequent service operation. Redesign for this upgrade impacts the LIM and inverter and possibly the power supply.

12.1.7 Automatic Train Control

- The Chubu experience with train control has been primarily based on their experience with the relatively short track, simple shuttle service of expo-type operations. Although the system as currently installed at the Nagoya test track is an automatically aided manually operated system, it appears to have many of the features needed for fully automated train control. However, the FTA team is not aware that fully automated operation has been demonstrated. The FTA requirements call for a full automatic operation of the Maglev system.

- It is understood that the driver's station will be eliminated for the planned Tobukyu Aichi Prefecture system. The driver's operational role must be integrated into the ATO system. The details of the full automatic control system architecture need to be supplied and evaluated. In particular, the safety-critical thrust controller architecture must be provided. Additionally, there are still a number of questions, which will require further inquiry of the exact roles and operation of the various functions contained within the current and envisioned changes to the automatic train control system.

- Finally, a risk assessment must be provided on the complete automatic control system as it will be used in the U.S. The safety risk assessment must also include all safety-critical systems incorporated into the CHSST.

12.2 Recommendations

A number of comments and recommendations have been made in each of the chapters of this report for potential improvements to the CHSST system to satisfy the U.S. mandatory and FTA requirements. An outline plan of action on the recommendations is presented in the following paragraphs for consideration by the FTA and MUSA.

It is clear that some of the FTA system requirements are both generic and site specific. Even then, the CHSST Maglev will need some upgrades and design modifications to meet the U.S. mandatory and the FTA requirements. The FTA team recommends the following measures be taken by MUSA/CHSST to enable their system to be deployable in the U.S. These measures are based on near, intermediate and long term time perspectives.

12.2.1 Near Term (0-1 year)

The purpose of the near term work is to provide clarification and additional analysis and test data on technical issues raised in this report, including:

- Analyze the guideway structure and component life for 160 kph operation in view of the fact that the guideway permanent structure is expected to serve for 75 years. Also, analyze the life of attachments and the impact on maintenance strategy and cost.

- Estimate the frequency of inspections, and associated costs for correcting guideway irregularities.

- Analyze the vehicle dynamic behavior under worst possible combinations of guideway tolerances, and ensure that no instabilities occur and the FTA ride quality requirement is satisfied at least at 130 kph speed.

- Provide justification for the 20 year vehicle life and estimate the proportion of life consumed due to fatigue/wear and corrosion/degradation. Indicate how the life can be extended to 30 years without increasing the size of the vehicle structural members and hence, its weight.

- Evaluate the crashworthiness level of the vehicle as it exists. Provide design approaches to improve the crashworthiness without significant increase in weight. Account for both standing and seated passengers in these evaluations.

- Evaluate the egress and rescue capability for the existing vehicle design under smoke and fire conditions and determine methods of improvement.

- Analyze the reliability of the levitation guidance system and suggest methods of improvement.

- Re-examine the LIM design, including its control system, and identify cost effective means of increasing thrust capacity by substituting the aluminum winding with copper or by other means, with the target of reaching full speed capability on 7 percent gradients.

- Re-examine the caliper brakes in light of noise and vibration apparently generated in their application as discussed in this report. Because the braking distances of the present CHSST are longer than required in the FTA standards, show how an upgrade can be provided to remedy this situation.

- Analyze the system costs addressed in this report, and show how the costs, particularly the initial costs of the "basic" two-way elevated guideway, can be reduced to meet FTA expectations, or come close to those expectations.

- In order to more fully understand the chosen ATO system, the MUSA/CHSST team needs to furnish a fully documented description of the train control and communications systems, including system architecture, ATO hardware implementation, identification and operational descriptions of safety critical elements that demonstrates the ability of the CHSST system to provide safe and fully automated operation. The description also needs to include present headway capability as well as the changes, if any, needed to operate with headways of 100 seconds or less.

12.2.2 Intermediate Term (1-2 years)

The purpose of activities over this term will be to identify suitable deployment situations in the U.S. and to analyze and test CHSST vehicles at a peak speed of 130 kph. As noted in this report, some components would require redesign to meet with U.S. mandatory requirements and FTA desired performance.

- Evaluate the market potential at possible specific locations in the U.S. Identify those urban locations and routes for which the redesigned system's characteristics are suitable, i.e., maximum speed of 130 kph, minimum turn radius of 25 m for 100-S and 50 m for 100-L vehicles, etc. Select the most promising candidate site and perform sufficient route studies from which cost realistic cost estimates can be developed.

- Determine system level capital and operating costs for the candidate site, and potential revenues during operation. Compare the costs with competitive systems of equivalent performance for the selected route location.
- Identify and obtain potential interest, support and commitments from financial partners' and from the appropriate local, state, and federal government entities.
- Provide a comprehensive analysis and a list of key issues for the CHSST to run at 130 kph. Re-evaluate the system performance and safety for this speed by testing.
- Redesign the interior layout of the seating to satisfy the U.S. ADA mandatory requirements. Re-evaluate system passenger capacity after the redesign and determine measures required to satisfy the passenger capacity goal of the FTA while accounting for U.S. space requirements.
- Design one or more alternate cost effective and more efficient switches for the CHSST system.
- Re-assess the vehicle weight savings achievable through alternate construction and design changes as appropriate.
- CHSST needs to evaluate and demonstrate all-weather capability of their ATO system to operate under U.S. environmental conditions and thus provide all-weather operational capability.

12.2.3 Long Term (>2 years)

The purpose of the long-term activities is to assure the readiness of the CHSST system for deployment in the U.S.

- Monitor the progress in Nagoya on the technology, financing and construction for the proposed 9.2 km Tobukyu revenue line. Upgrade the proposed system in the U.S. on the basis of any relevant improvements and experience gained in Japan. Some additional testing specified in this report can possibly be carried out on the Tobukyu guideway proposed in Japan. The Tobukyu Line signal system may not be designed for speed of 130 kph and the Nagoya test track may be too short for 130 kph runs. MUSA and CHSST should examine this issue of 130 kph test demonstrations.
- Test, evaluate and perform endurance tests on a suitable test track the design changes implemented of a CHSST system suitable for deployment in the U.S.

- A fully automatic train control system provides the principal means of longitudinal control and safety. Therefore, an independent safety risk assessment consistent with current DOT guidelines must be performed prior to the CHSST being given approval for operation in the U.S. This assessment also should provide independent validation and verification of all the safety-critical control functions.

- Develop financial partnership and deployment plans for the selected route(s) in the U.S.

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