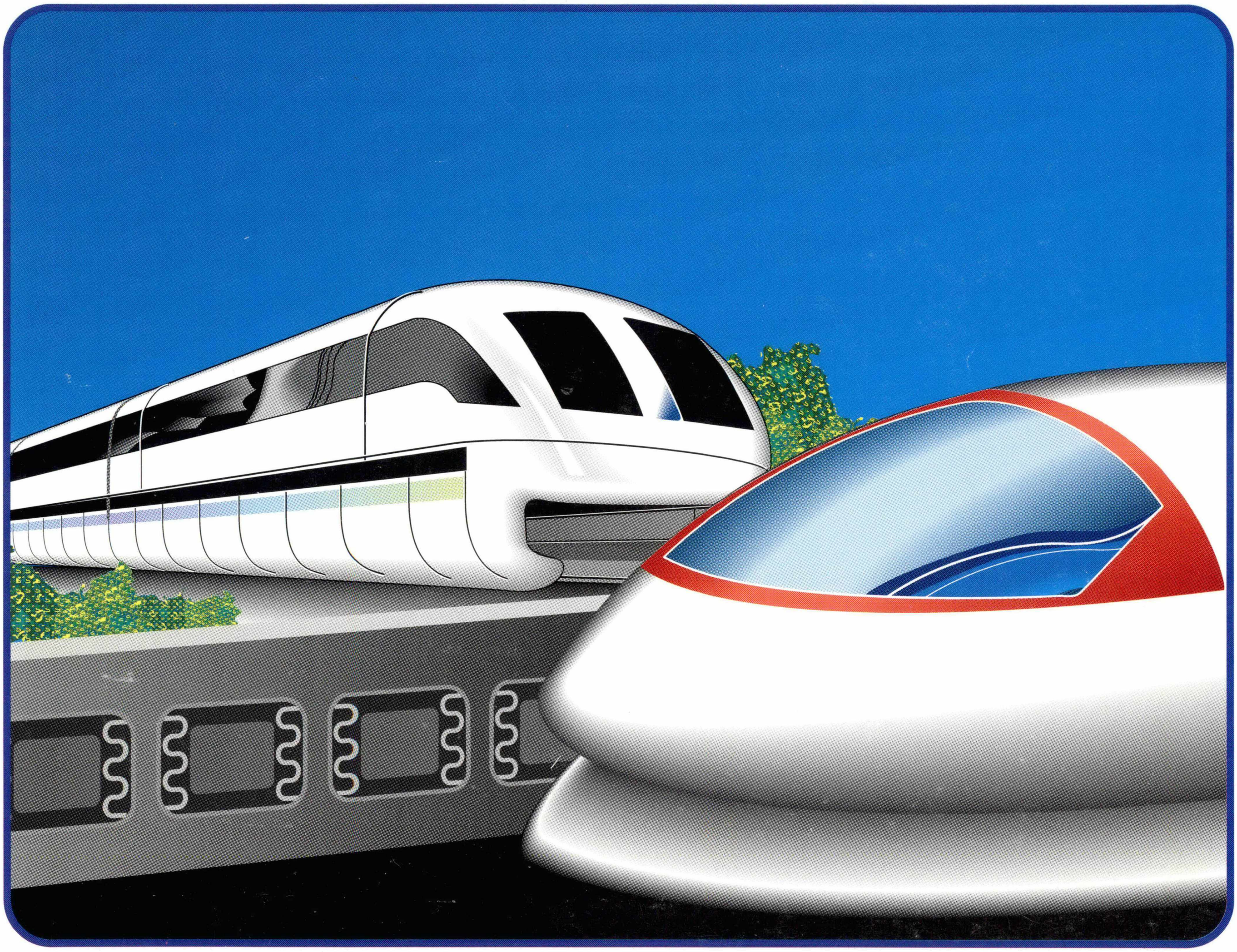
U. S. Department
of Transportation

Federal Railroad Administration

Safety of High Speed Magnetic Levitation Transportation Systems

Preliminary Safety Review of the Transrapid Maglev System



Moving America
New Directions, New Opportunities

April 1991

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In numerous places, this report discusses whether various aspects of the technology that is the subject of this report comply with Federal safety laws and regulations. Those discussions, which reflect the seasoned judgement of commentators qualified in their fields, do not consitute rulings by the Federal Railroad Administration's Office of Safety or its Office of Chief Counsel concerning compliance with the law.

FOREWORD

The use of magnetically levitated (maglev) vehicles for high speed guided ground transportation could easily become a reality in this decade. The first such system will likely be the Florida Maglev Demonstration Project in Orlando. A result of this encouraging development is that there exists a need for the assessment of the safety aspects of this new form of guided ground transportation. This requirement is the responsibility of the Federal Railroad Administration which is charged with the safety of maglev systems in the United States in the Rail Safety Improvement Act of 1988.

The first in a series of reports that will address high speed maglev transportation safety, this Executive Summary and its companion report illustrate the system safety approach that will be taken as the maglev safety evaluation project develops. This and future studies will focus initially on the German Transrapid electromagnetic (or attractive) technology. Further studies will review maglev safety standards, operations and maintenance guidelines and the certification testing used in Europe. Safety verification test requirements will also be established for new U.S. installations. Before FRA's multiyear safety assurance program is complete, both the electromagnetic (attractive) and electrodynamic (repulsive) maglev technologies will have been covered.

There is no doubt that our current level of understanding of the Transrapid system would not have been possible without the excellent cooperation of the Federal Ministry for Research and Technology, TÜV Rheinland, the Transrapid Consortium and the Versuchs und Planungsgesellschaft für Magnetbahnsysteme mbH (the test and planning organization for maglev systems) all of the Federal Republic of Germany. Their openness has provided a vast amount of technical data and the opportunity to observe developmental testing of the Transrapid system.

At the Federal Railroad Administration we are dedicated to ensuring public safety in the field of guided ground transportation through constant vigilance over new developments. We strive to accomplish this without inadvertently impeding project progress in implementation of these new technologies.

With this in mind, we are actively engaged in working with new system developers and planners through the conduct of project accompanying safety assessments. We realize that the safety of high speed surface systems must be built in from the beginning -- "designing the accident out" is just good engineering. Safety issues raised early in this assessment process should therefore only be considered an alerting mechanism that will help insure adequate attention is directed to the identified areas of concern during a project's developmental phase.

Frequently, issues raised in our safety assessments are already being attended to by the developer and resolution of the problem has been met by time it has been reported. This very occurrence speaks well of the effectiveness of FRA's proactive safety stance in working hand-in-hand in a public/private partnership with industry to achieve the safest possible guided ground transportation environment.

Gil Carmichael

Gilbert E. Carmichael
Administrator

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INTRODUCTION

This Executive Summary of the first interim report, *Safety of High Speed Magnetic Levitation Transportation Systems*, presents a preliminary safety review of the Transrapid Maglev System intended for use in Orlando, Florida and between Anaheim, California and Las Vegas, Nevada. The study was conducted as a peer review of the work of others to identify safety issues presumed to exist at the time of this review and the hazards which can lead to them.

It includes reviews of relevant Federal regulations and industry practices in the U.S. and compares them to proposed foreign standards to be met by the Transrapid system in its application in the Federal Republic of Germany. Current U.S. and proposed foreign standards are compared for similarities, differences, appropriateness, applicability and omissions with respect to the maglev transportation system technologies involved.

Modifications to existing regulations, standards from rail and other industries that may be adopted and recommendations for new regulatory efforts based on the study "findings" address safety issues identified up to this point.

THE FEDERAL RAILROAD ADMINISTRATION's ROLE IN REGULATING MAGNETIC LEVITATION

The Rail Safety Improvement Act of 1988 made clear the jurisdiction of the Federal Railroad Administration (FRA) by defining the term railroad to include: "all forms of non-highway ground transportation that run on rails or electromagnetic guideways, including: (1) commuter or other short haul rail passenger service in a metropolitan or suburban area; and (2) high speed ground transportation systems that connect metropolitan areas without regard to whether they use new technologies not associated with traditional railroads."

FRA Regulations

The FRA promulgates the necessary regulations to achieve its rail safety charter. These regulations are published in the Code of Federal Regulations (CFR) and currently consist of CFR Part 49: sections 173, 174, 179 and 200 through 268. The CFR regulations that relate to safety tend to be technology specific and based on years of railroad operating experience. Nevertheless, some of these regulations can be applied directly or have their intent adapted to maglev guided ground transportation.

In addition to the CFR regulations, the FRA also relies on guidelines (i.e., Fire Safety), industry standards and practices like the Association of American Railroads' (AAR) *Manual of Standards and Recommended Practices* and *Field Manual of A.A.R. Interchange Rules*, and the American Railway Engineering Association's (AREA) *Manual for Railway Engineering*. These industry standards tend to be detailed specifications for conventional railways and are not performance based. Thus, in most cases it may prove difficult to apply them to maglev systems.

Non-Railroad Federal and Industry Standards

Other potential guidance can be found in Federal regulations and industry standards for transportation systems with similar attributes. For example, the Federal Aviation Administration (FAA) has windshield strength standards for airplanes that, although different from the FRA's locomotive windshield standards, may have some relevance to maglev. Some of the Urban Mass Transportation Administration's (UMTA) emergency preparedness procedures for rail transit systems may also be relevant. Various Department of Defense (DOD) standards such as MIL-STD-882B, System Safety Program Requirements, also contain valuable information that may be applied. Industry (as well as FAA) standards in software verification and control for "fly-by-wire" planes may be adapted to the automated control systems required by maglev vehicles.

U.S. PERSPECTIVE

Transrapid maglev technology is currently being considered for construction in several different corridors in the United States, as well as in Germany. A demonstration project in Florida is the most advanced of the various proposed projects.

In 1984, the Florida legislature established the Florida High Speed Rail Transportation Commission (FHSRTC). The FHSRTC was charged to "implement the innovative mechanisms required to effect the joint (public and private) venture approach to planning, locating, permitting, managing, financing, constructing, operating and maintaining an interregional high speed rail line for the state, including providing incentives for revenue generation, operation and management by the private sector." In 1988, the Florida legislature passed the Magnetic Levitation Demonstration Act and assigned responsibility for this effort to the FHSRTC as well.

The Maglev Transit, Inc. (MTI) proposal being considered will link the Orlando International Airport to a point west southwest of the airport on International Drive (a length of approximately 13.5 miles) using the Transrapid maglev system in a shuttle operation. The proposed single guideway will be elevated for most of the route.

In addition to the Florida demonstration project, Transrapid maglev technology may be used in several other corridors like the Los Angeles (Anaheim) to Las Vegas route and the Pittsburgh to Harrisburg route. The potential use of maglev on longer intercity routes adds some safety issues that are not directly involved in the Florida demonstration project. These include the implications of double tracking guideways or single track guideways with long passing sidings in operation; the high speed passing of maglev trains in the open and in tunnels; the entering of tunnels by high speed vehicles and the high speed traverse of maglev switches.

Another major difference in intercity routes is the need for the control system to be capable of safely handling more than one moving train on the same guideway at a time. Issues such as how multiple trains can be stopped and evacuated safely during systemwide emergency shutdown, if necessary, must also be considered in these applications.

SAFETY EVALUATION

The safety goal of a transportation system is to provide patrons and employees with the highest level of safety practical. To achieve this goal requires safety to be a primary consideration throughout the system life cycle. The safety analysis method used by FRA for this maglev evaluation is the System Safety Concept.

THE SYSTEM SAFETY CONCEPT

The system safety approach applies special technical and managerial skills to systematically identify and control hazards throughout the life cycle of a project, program or activity. This approach calls for safety analyses and hazard control activities to begin with the preliminary design phase and to continue through the operation phase. Figure 1 depicts this hazard resolution process.

DEFINE THE SYSTEM

- DEFINE THE PHYSICAL AND FUNCTIONAL CHARACTERISTICS TO UNDERSTAND AND EVALUATE THE PEOPLE, PROCEDURES, FACILITIES AND EQUIPMENT, AND THE ENVIRONMENT

IDENTIFY HAZARDS

- IDENTIFY HAZARDS AND UNDESIRED EVENTS
- DETERMINE THE CAUSES OF HAZARDS

ASSESS HAZARDS

- DETERMINE SEVERITY
- DETERMINE PROBABILITY
- DECIDE TO ACCEPT RISK OR ELIMINATE/CONTROL

RESOLVE HAZARDS

- ASSUME RISK OR
- IMPLEMENT CORRECTIVE ACTION
  - ELIMINATE
  - CONTROL

FOLLOW-UP

- MONITOR FOR EFFECTIVENESS
- MONITOR FOR UNEXPECTED HAZARDS

FIGURE 1. HAZARD RESOLUTION PROCESS

The advantage of the system safety approach is that it provides the opportunity to identify hazards early in the life cycle and to recommend any design and operational modifications necessary to ensure safety. Doing this prior to final system development, construction and operation serves to enhance safety and minimize cost. The focus at this early, preproduction stage of the maglev system is on prevention of accidents by eliminating and/or controlling safety hazards. This preventive approach makes the most effective use of resources and will serve to reduce the risks from system hazards to the lowest practical level.

The first step in hazard resolution is to define the physical and functional characteristics of the system. These are presented in terms of the major elements which make up the maglev system:

- Equipment and facilities,
- Procedures,
- People, and
- Environment.

The second step in the process is to identify hazards and determine their causes. When identifying the safety hazards in a system, a major concern is that only a portion of the total number will be uncovered. The type and quality of the hazard analysis will influence the relative number of hazards identified. There are four basic methods that may be used. These are:

- Analysis of operating experience or data from previous accidents, tests or case studies. (not readily available for maglev.)
- Scenario development and judgment of knowledgeable individuals (expert opinion, or use of the Delphi Approach).
- Use of generic hazard checklists.
- Formal hazard analysis.

Step three in the hazard resolution process is to assess the identified hazards in terms of the probability (P) of occurrence and severity of the expected consequence (C). The combination of probability and consequence determines the risk.

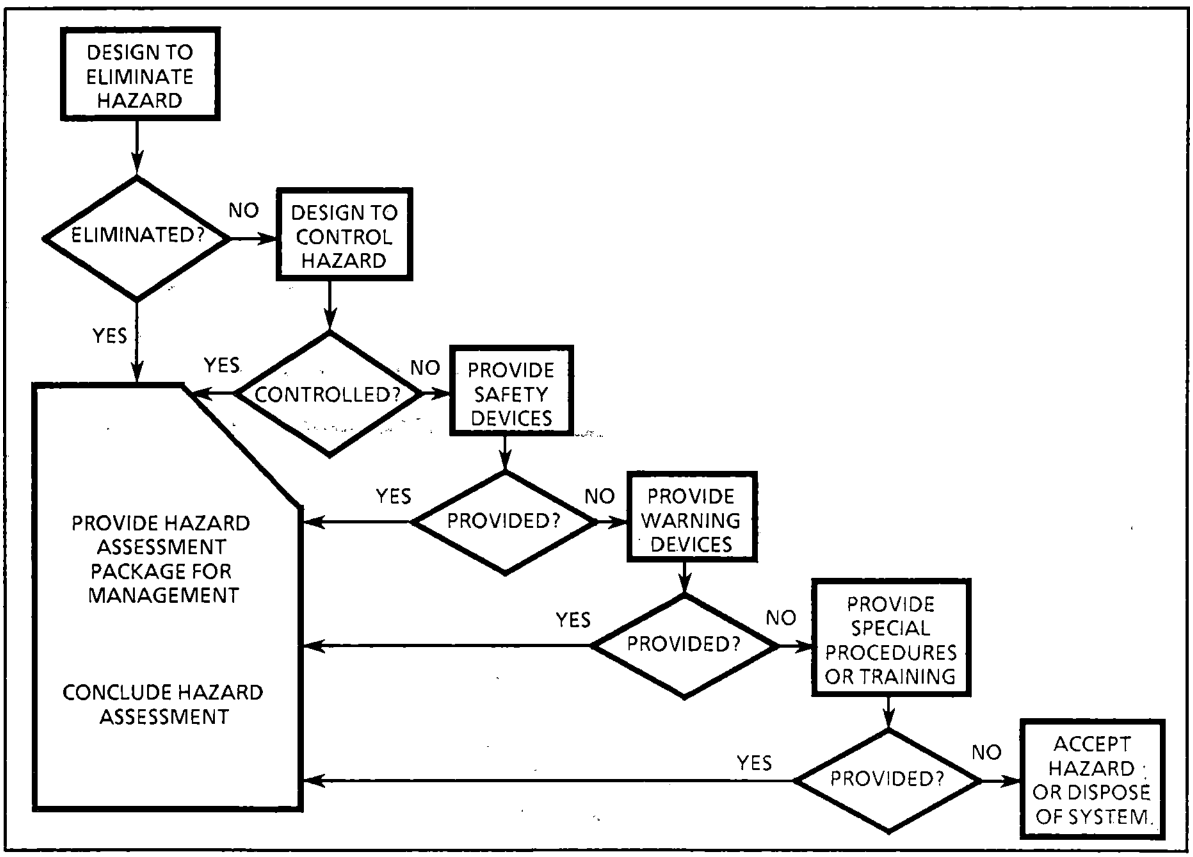
After the hazard assessment phase is completed, hazards can be resolved (step 4) by deciding to accept the level of risk, to eliminate it or to control it. Various means can be employed to reduce the risk to a threshold acceptable to management.

Figure 2 presents a process that can be used to determine the extent and nature of preventive actions that can be taken to reduce risk to an acceptable level. Resolution strategies, or countermeasures, in order of preference, include the following:

- Design to Eliminate Hazards
- Design to Minimize Hazards
- Provide Safety Devices
- Provide Warning Devices
- Provide Procedures and Training
- Accept Risk or Replace/Dispose of System

In this preliminary study, risk countermeasures were developed to address the undesired events identified by hazard scenarios, hazard checklists and formal analyses (see "Potential Maglev Safety Issues" section). The "Resolution of Maglev Safety Issues" section assesses hazard control or countermeasure effectiveness. It also discusses options for maglev hazard resolution and recommends FRA regulatory safety requirements.

The last step in the hazard resolution process is to follow up. The effectiveness of hazard prevention and control must be monitored to ensure that new hazards are not introduced as a result.



Source: Roland & Moriarty, *System Safety Engineering and Management*, 1983

FIGURE 2. HAZARD REDUCTION PRECEDENCE

TR-07 DESCRIPTION

The Transrapid TR-07 is the latest evolution in the development of an electromagnetically suspended vehicle designed to cruise at speeds of 400 to 500 km/h (250 to 312 mph). It operates with an air gap of 8 mm (0.315 in.) and uses attractive magnetic forces for both suspension and guidance. The magnetic suspension is bolstered by a secondary air suspension to improve ride quality. The TR-07 uses a linear synchronous motor (LSM) constructed as part of the long stator guideway to provide propulsion and braking.

The TR-07 train (figure 3) is comprised of multiple joined sections, each section having a length of 25.5 meters (84.2 feet), a weight of 45 metric tons (45.5 tons) and a payload of 16 metric tons (100 passengers or 16.2 tons). Trains can be configured for bidirectional operation (as in this case with an operator's control station at each end). Sections (without the operator's console) can be added or removed between the ends to adjust passenger capacity.

The Transrapid suspension system wraps around the guideway in a manner that effectively captures it. An important design feature is the uniform distribution of suspension and guidance magnets over the length of the vehicle. This produces an even loading of the guideway with less potential stress in the guideway girder.

Guideways are usually elevated and built with welded steel or concrete spans of 25 to 50 meters in length (figures 4 & 5). Support substructures are either A-shaped or slim-line ("H") concrete columns (figure 6). In special sections, at-grade guideways of approximately 12 meter lengths are used. Final fitting of the beams onto the guideway supports is performed on site by computer aided measurements, as alignment is critical.

A central control facility maintains automated control of train operations during normal conditions and most emergencies. Vehicle propulsion and braking are controlled by varying the excitation voltage and frequency of the guideway mounted linear synchronous motor. Detection of vehicle position and the transmission of data/voice is accomplished by on board vehicle electronics and devices; other functions, such as route control, vehicle control, station supervision and control, and communications are accomplished through decentralized wayside equipment as coordinated and controlled by the central control facility.

Failure tolerant operation is an important requirement for acceptance of the high speed maglev system. Automatic control is essential to achieve fault tolerant operation at the envisioned speeds. System components must

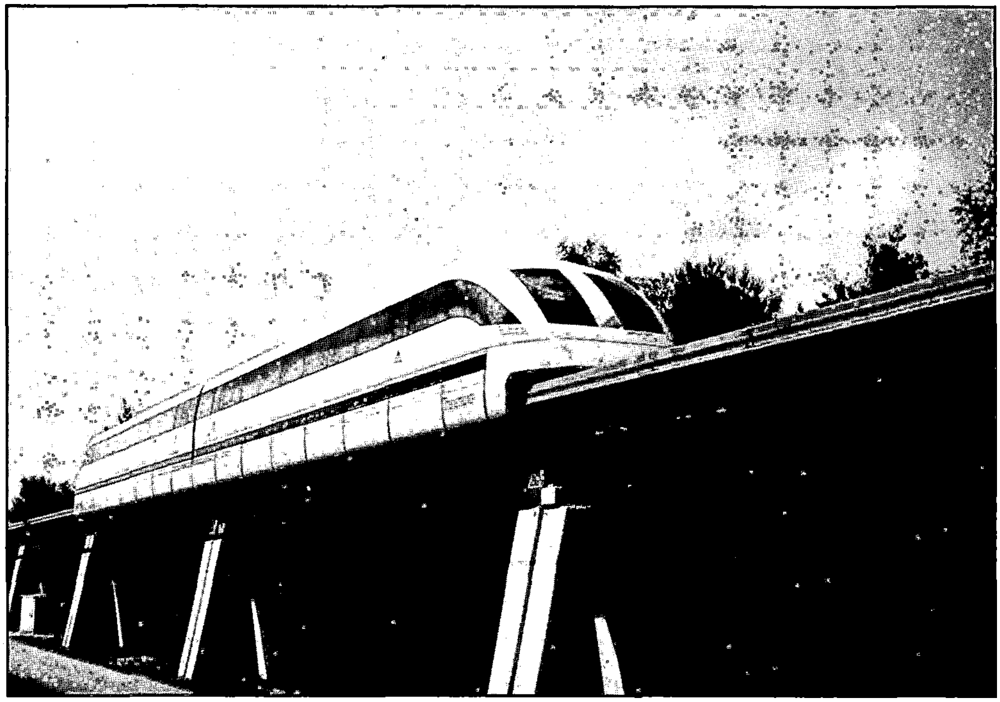


FIGURE 3. TR-07 TWO CAR TRAIN

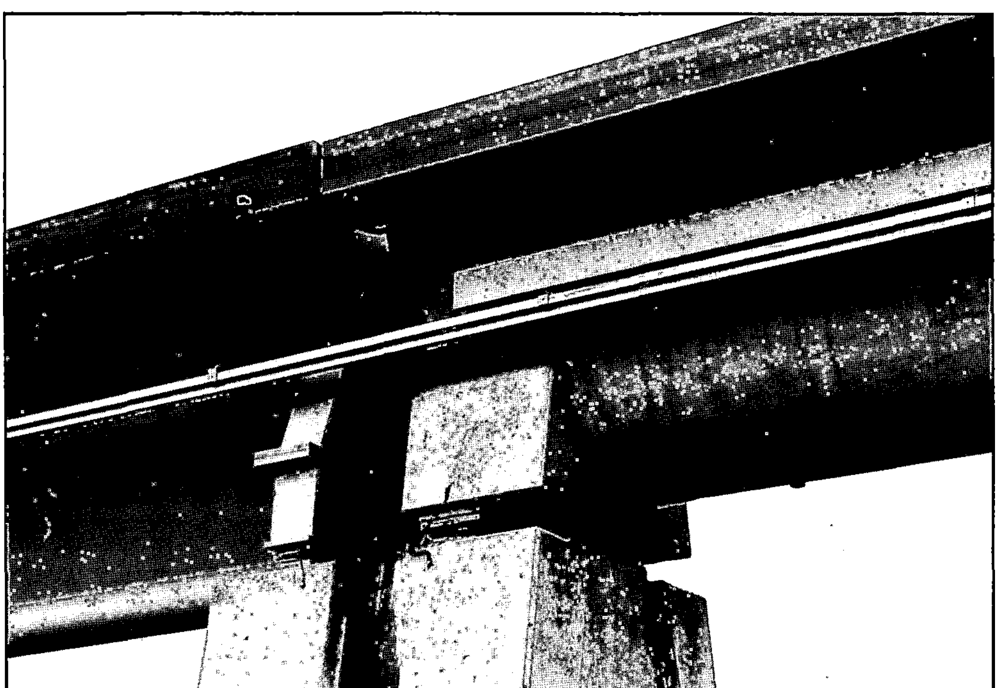


FIGURE 4. STEEL AND CONCRETE SPANS

have high mean time between failure (MTBF). Critical circuits must be made sufficiently redundant to ensure high system availability.

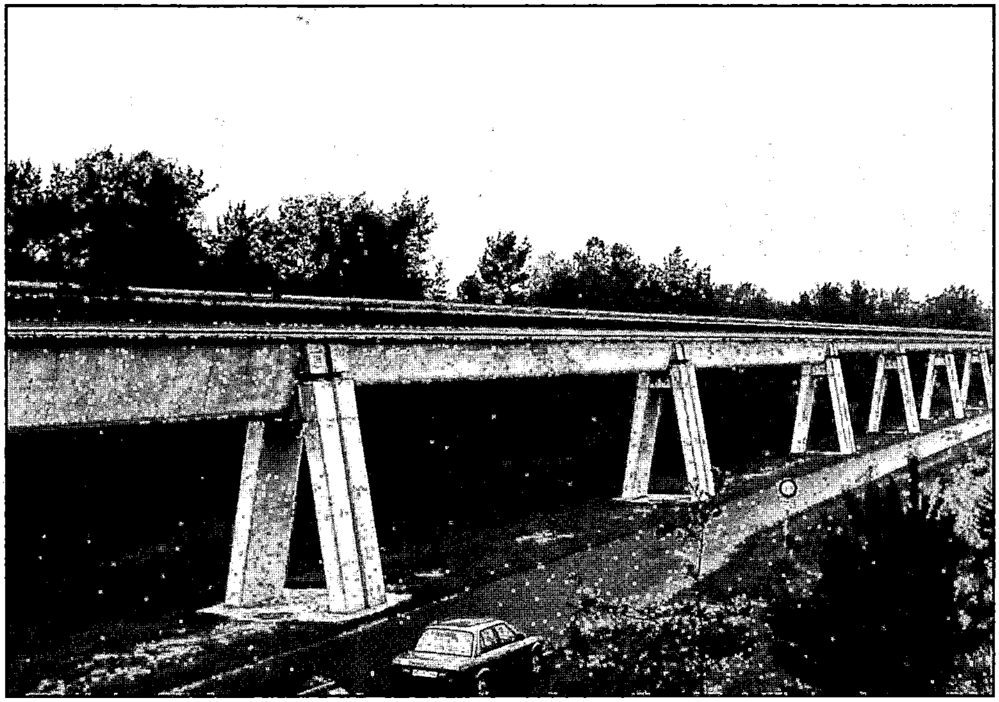


FIGURE 5. SPAN DEPTH VARIES WITH LENGTH

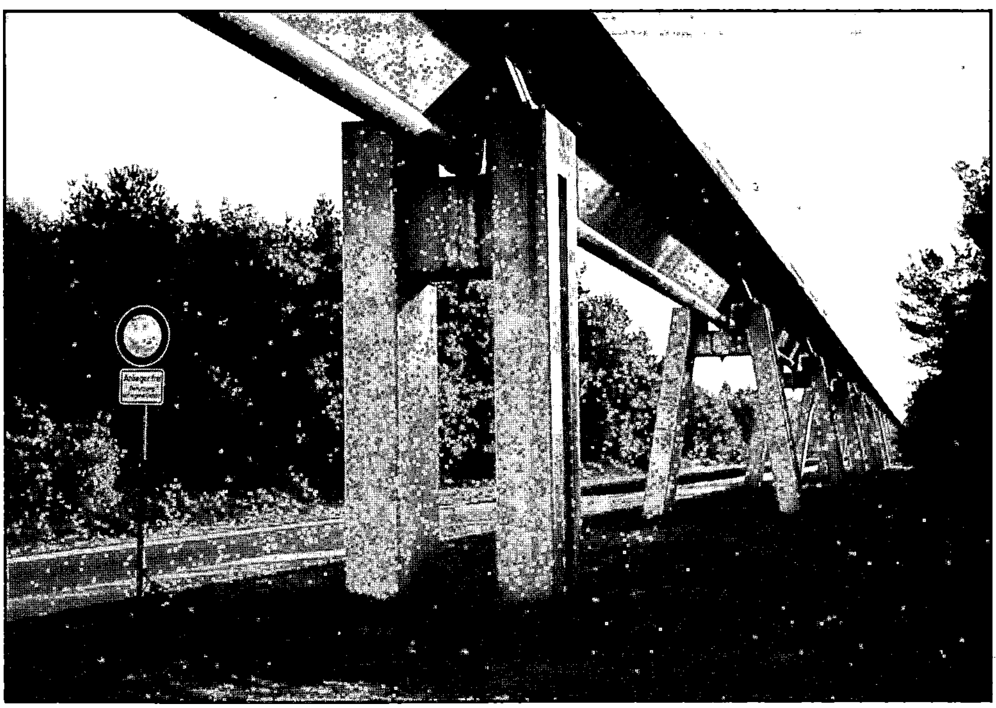


FIGURE 6. "A" AND "H" COLUMNS

SAFE HOVERING

Uncontrolled vehicle contact with the guideway is considered unacceptable. To prevent this, the manufacturer has designed a system to preclude total loss of the levitation and guidance subsystems. The German High Speed Maglev Trains Safety Requirements state that the vehicle levitation and guidance functions shall not be lost for any combination of system failures. Further, the vehicle must be able to maintain its own suspension until it is brought to a stop by central control or its internal control system. This requirement is known as "safe hovering" (levitation).

Safe hovering requires a high level of reliability. Designers have attempted to achieve this reliability through design redundancy and use of minimum acceptable values for mean time between failures (MTBF) of critical components. The manufacturer uses redundant systems for both levitation and guidance.

The Transrapid safe hovering concept requires that the vehicle come to a stop only at guideway locations where auxiliary power and evacuation means are provided. The following five requirements are listed by the developer to ensure "safe stopping areas" are always reached.

(1) The vehicle must develop enough speed when leaving a station so it can reliably coast (without propulsion) to the next allowed stop location.

(2) The vehicle must be able to reach the next allowable stop location independent of wayside power (i.e., only by on-board battery power).

(3) The safe hover and safe stopping systems must attain the reliability, by electrical and physical autonomy, to limit the risk of multiple failures to an acceptable level.

(4) The vehicle must be able to come to a stop at a safe stopping location without any input or guidance from the central control system.

(5) The vehicle control system reliability must ensure safe operations independent of the central control system.

AUTOMATIC TRAIN CONTROL (ATC)

The Transrapid signal and control system is a fully automated system designed to ensure train operating safety. It serves the two basic functions of: (1) maintaining vehicle speed within operating specifications (safe speed enforcement), and (2) providing a safe and unobstructed travel path (route integrity).

Effective braking is vital to guarantee controlled deceleration in an emergency. The primary brake is actuated by the central control system. Propulsion current is simply switched to produce reverse thrust. Thus, the initial response to an emergency is begun by central control.

Speed Control (Safe Speed Enforcement)

TR-07 control relies on microprocessors at central control, at distributed wayside control locations and on the vehicles. These microprocessors are designed, implemented and verified with several fail safe, fail active and fault tolerant techniques for hardware and software. In addition, a variety of sensors are used to verify vehicle location, switch position, local wind speed and exterior temperature.

Predetermined speed profiles and operating scenarios are stored in the central control computer files. The central control operator selects the appropriate one. Once the desired speed profile or operating scenario is chosen, it is automatically transferred to the unmanned wayside control points for coordination of vehicle propulsion and braking. The vehicle control computer is continuously updated with information (like vehicle position and safe stop locations) via its data link to central control. This permits the vehicle to stop at the next available safe stop location at any time without further information from the central or wayside control.

Position Control (Route Integrity)

The route integrity portion of the control system determines if the route requested by the system operator at the central control is safe. Once the speed profile is chosen, the wayside control elements verify the necessary route. Before "proceed" authority is granted, the condition of the requested route switch positions and location of other vehicles is checked. All position and end locking sensors must register the correct position for the switch to be deemed "in place." The switch is kept in place by a mechanical lock. When predetermined switch position requirements and guideway occupancy conditions (i.e., safe headway between trains) are met, authority is given by the route integrity portion of the control system to the control elements governing the propulsion systems. After a route is cleared for operation and operation commences, the safe speed enforcement portion of the control system monitors vehicle speed to maintain it within the specified profile.

FACILITIES

Central Control

Central control serves as a base for the staff assigned to handle traffic timetables and line information. The center houses high capacity computers and peripheral equipment responsible for supervision of the moving vehicle (route control) and for the display of traffic information. The traffic displays allow the staff to monitor activity and discuss the need for corrective steps. Figure 7 depicts the control equipment at Emsland.

Normal traffic movement is handled automatically based on a stored timetable. The computer is able to adjust the timetable to accommodate minor disturbances in scheduled operations. However, operating staff can intervene and modify the timetable to change the traffic sequence as needed. Should major problems in scheduling occur, the operator can take measures to correct or bypass faults. Process computers in central control simulate the intended corrections to predict their effect before they are set into action.

Power Substations and Distribution

Power for the propulsion system is supplied by substations (typically spaced 6 to 18 miles apart) which convert 3 phase utility power into the variable voltage, variable frequency (VVVF) current required. The substation power is distributed to the guideway stator through a network of feeder cables.

The substations are dual power systems; each half of the substation has a transformer rectifier unit feeding a pair of 3 phase inverters. The inverters adjust the voltage frequency and phase so that the field generated by the propulsion windings varies relative to the magnetic field produced by the vehicle coils. This is how vehicle thrust is produced and controlled. The substations are sized so that either half can power the vehicle at reduced speed to the next station.

VEHICLE

The TR-07 is operated as a train of multiple coupled cars with nose sections at each end. Each section has a capacity of about 100 passengers. The dimensions and weights of the TR-07 cars are listed in Table 1.

The coach body performs several functions. The enclosure, with equipment for heating and cooling, provides a protective and comfortable housing for passengers. As a load carrying member it provides a path for stresses to be transmitted to the suspension. Finally, the external shape can be streamlined

TABLE 1. TR-07 VEHICLE DATA

CHARACTERISTIC	TR-07 DATA
Coach Body Length (single end section)	25.5 (m)
Coach Body Width	3.7 (m)
Overall Height	3.95 (m)
Height Above Floor Edge	2.27 (m)
Coach Body Carcass Weight (single end section)	5,173 (kg)
Tare Weight (two end sections)	90 (t)
Payload (two end sections)	16 (t) 200 pass.
Support and Guidance System	19.5 (t)

to minimize aerodynamic drag (and energy use).

Doors are located at the ends of the vehicle to increase stiffness. They are single wing, swinging/sliding doors with inflatable seals.

To meet passive fire protection standards, the interior furnishings meet the 1988 Air Transport Standards (five minute 1100° C [2012° F] fire without harmful fumes emitted, at 120° C [248° F] on the outside of the interior, vehicle cladding to protect the structure).

Suspension and Guidance

TR-07 suspension is divided into two stages, a primary and a secondary (see figure 8). The primary magnetic suspension closely follows the guideway

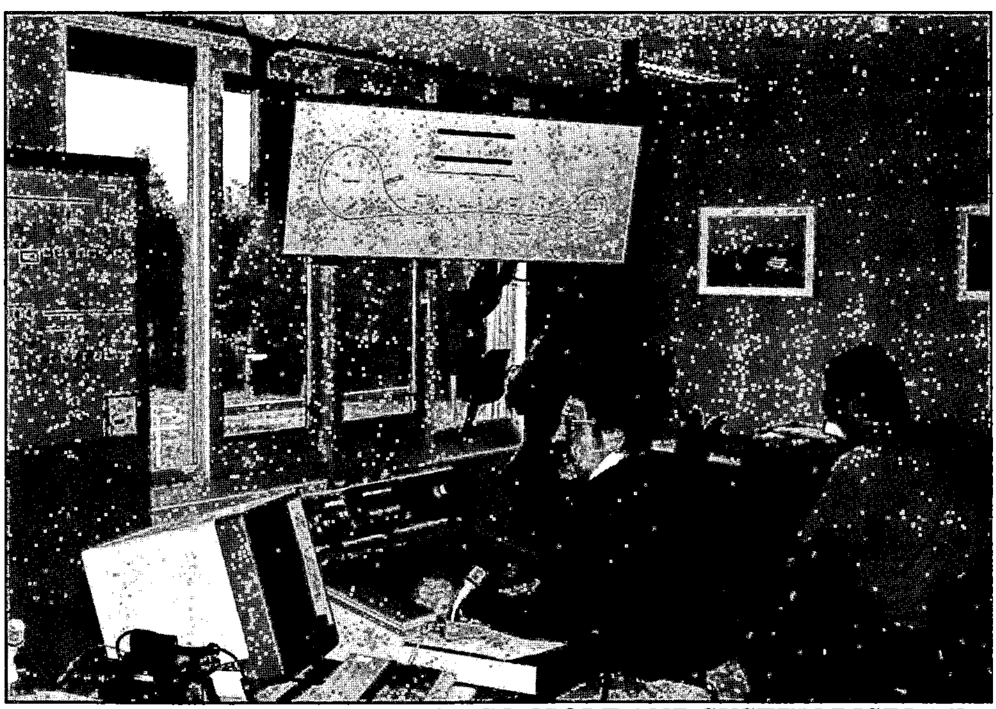


FIGURE 7. EMSLAND CONTROL CONSOLE AND SYSTEM DISPLAY

to support and guide the vehicle. It actively compensates for guideway irregularities. The secondary air suspension provides additional isolation of the vehicle body from the guideway to improve ride quality. Its purpose is to damp out magnetic suspension induced motions.

A separate set of vehicle magnets are oriented to produce a lateral attractive force on the guideway to steer the vehicle. Field strength is actively controlled to maintain an eight millimeter gap between the magnets and the guideway surfaces on both sides. Thus, it accurately reacts to direction changes.

Propulsion and Braking

Transrapid propulsion is produced by a linear synchronous motor (see figure 9). The vehicle, which acts as the rotor portion of the motor, contains the direct current field windings. They are mounted to result in a slight angle between their poles and those of the

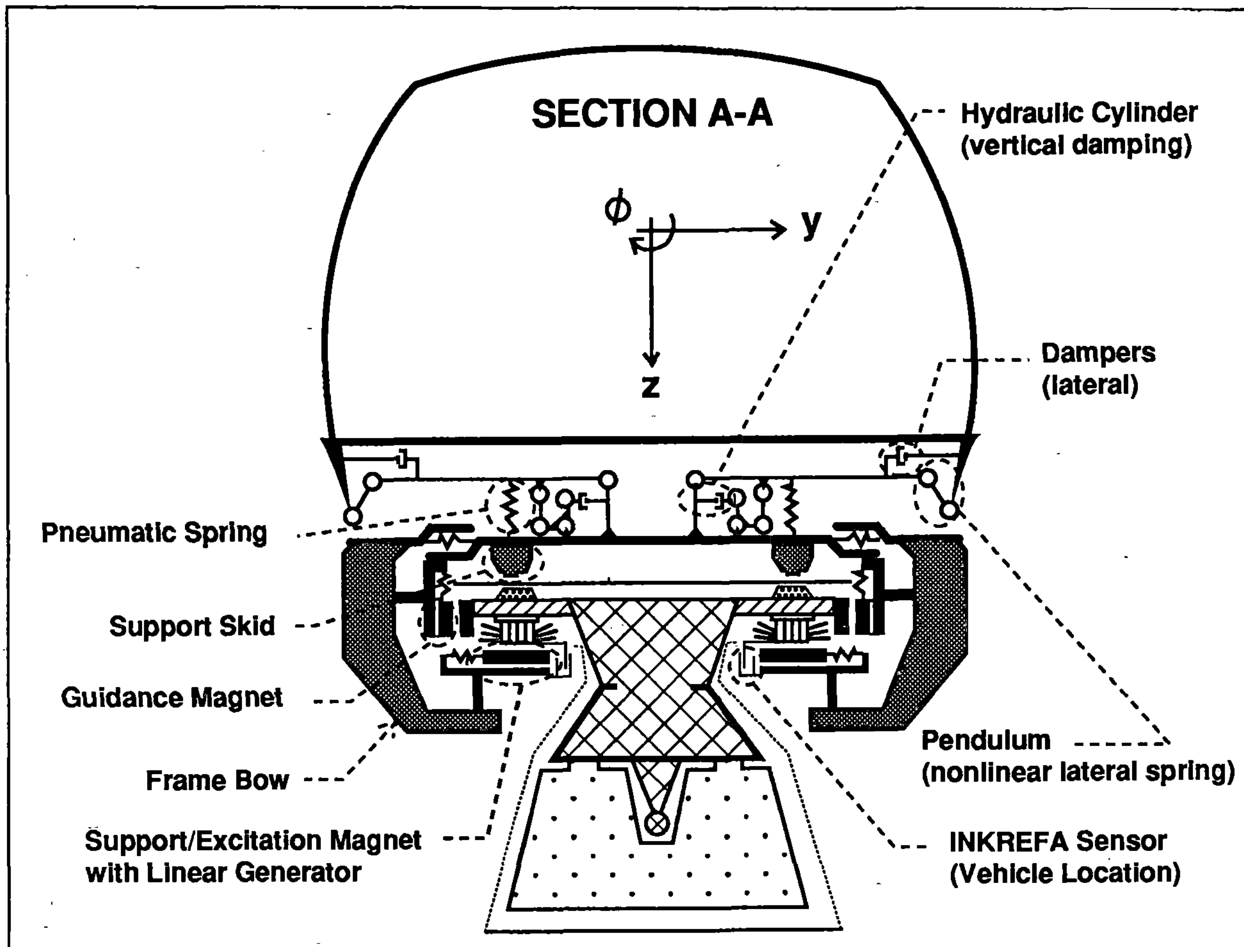


FIGURE 8. TR-07 SUSPENSION SYSTEMS

traveling magnetic field on the guideway stator. This creates a bias in the field interaction vector which provides directed vehicle thrust.

There are two methods of decelerating the vehicle, a primary and secondary braking system. The secondary brake functions independently of the primary and provides controlled braking should the primary brake fail.

The primary brake is actuated by the central control system. Propulsion current is simply changed to produce reverse thrust. Any electrical energy generated during vehicle braking is dissipated in load resistors at the substation.

The secondary brake uses the longitudinal vehicle guidance magnets to induce eddy currents in the track guide rails. The eddy currents create an electronic drag to dissipate the propulsion forces. Eddy current effect decreases sharply below about 50 km/h (31 mph), so final emergency braking requires the levitation magnets to be de-energized. The vehicle then slides to a stop on its composition landing skids.

At the German test track, the vehicle is programmed to settle on its skids at 120 km/h (74 mph) instead of the design speed of 50 km/h (31 mph). This increase in delevitation speed was required because of the effect of high magnetic forces on the guide rails. A stronger guide rail mounting designed

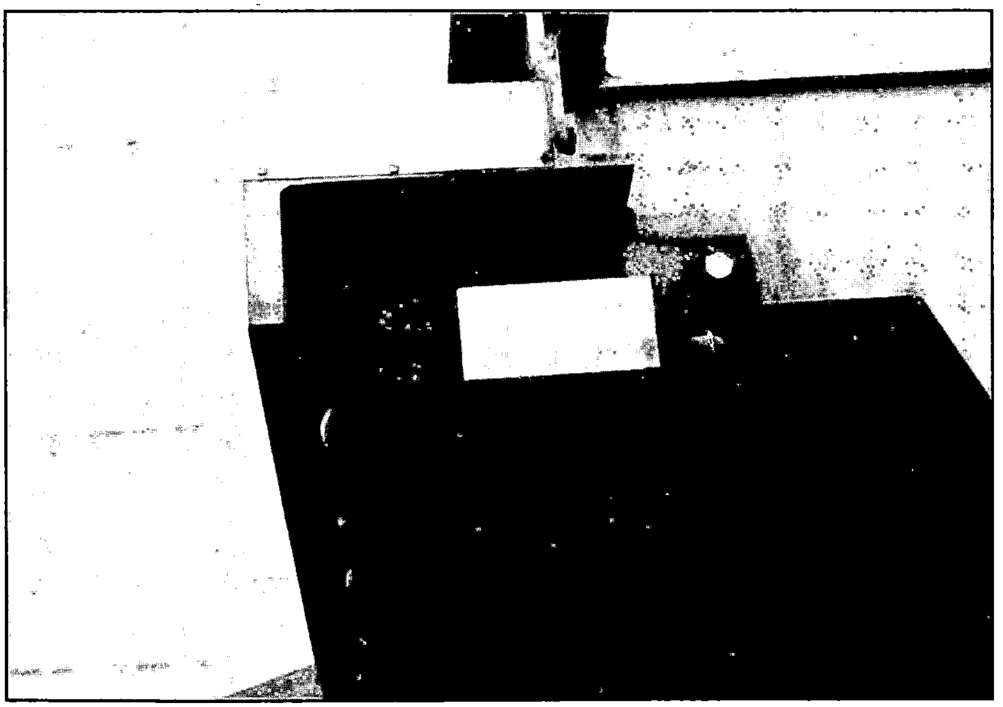


FIGURE 9. PROPULSION MOTOR - LONG STATOR MOUNTED UNDER THE GUIDEWAY

for the compressive loads of the TR-06 system is planned to allow for eddy current brake operation down to 50 km/h for proposed revenue service.

Vehicle Power

Transrapid vehicles contain on-board storage batteries that provide power independent of any external sources. Each vehicle section contains four electrically buffered 440 volt battery circuits. Batteries are recharged by power transmitted from the guideway through linear generators as the vehicle moves.

The linear generators provide non-contact power induced by the magnetic flux from the guideway long stator. Linear generator output is governed by the vehicle speed. Below 100 km/h (62 mph), the batteries supplement output from the linear generators to provide adequate power for operation; above this speed the linear generators provide all vehicle power as well as the recharging of the storage batteries.

GUIDEWAY

In tracked transport, the guideway is the stationary structure whose principal function is to bear the supporting and guiding vehicle loads. It can also contain electronically active elements which serve as an integral part of the system to control speed, start and stop functions of the vehicle. Since the vehicle is constrained to move in a line along the guideway, provisions are made to allow branching and merging of various routes by switch mechanisms.

Guideway Switch

As the path of a guideway diverges to two or more paths, a means is needed to switch a vehicle smoothly from one path to another. The Transrapid guideway accomplishes switching by having a guideway section bend to direct a vehicle to a new path. A hydraulic or electromechanical actuator bends the guideway at each movable span (figures 10 & 11).

The bending switch is designed with a box girder cross section that is continuously welded over multiple spans. Each span has a fixed support, supports with glide bearings or transverse support frames with two wheels, depending on how much lateral movement is required. The switch position is locked by actuating rods fixed through a knuckle joint. It is also locked by a braked drive motor and a self locking gear. Figure 12 shows the bending switch and support wheels.

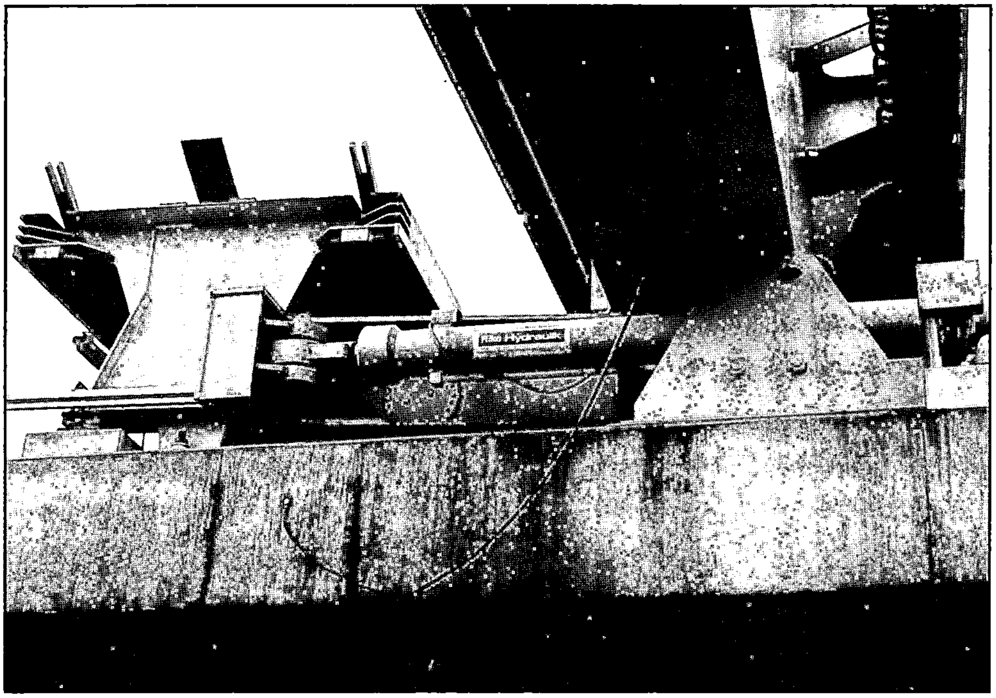


FIGURE 10. HYDRAULIC SWITCH

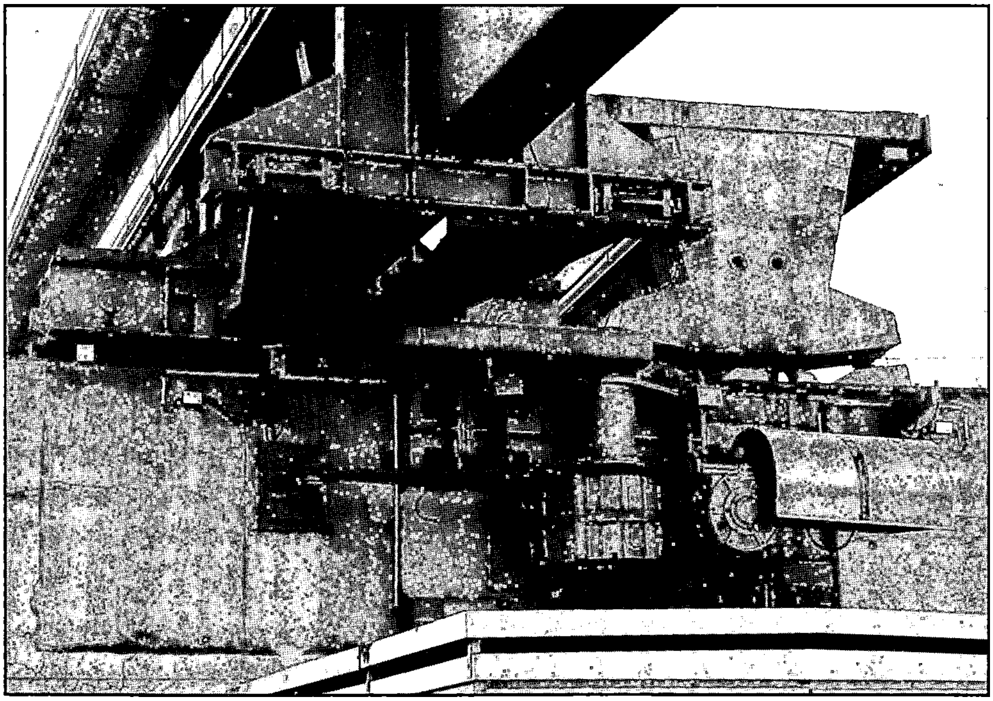


FIGURE 11. ELECTROMECHANICAL SWITCH

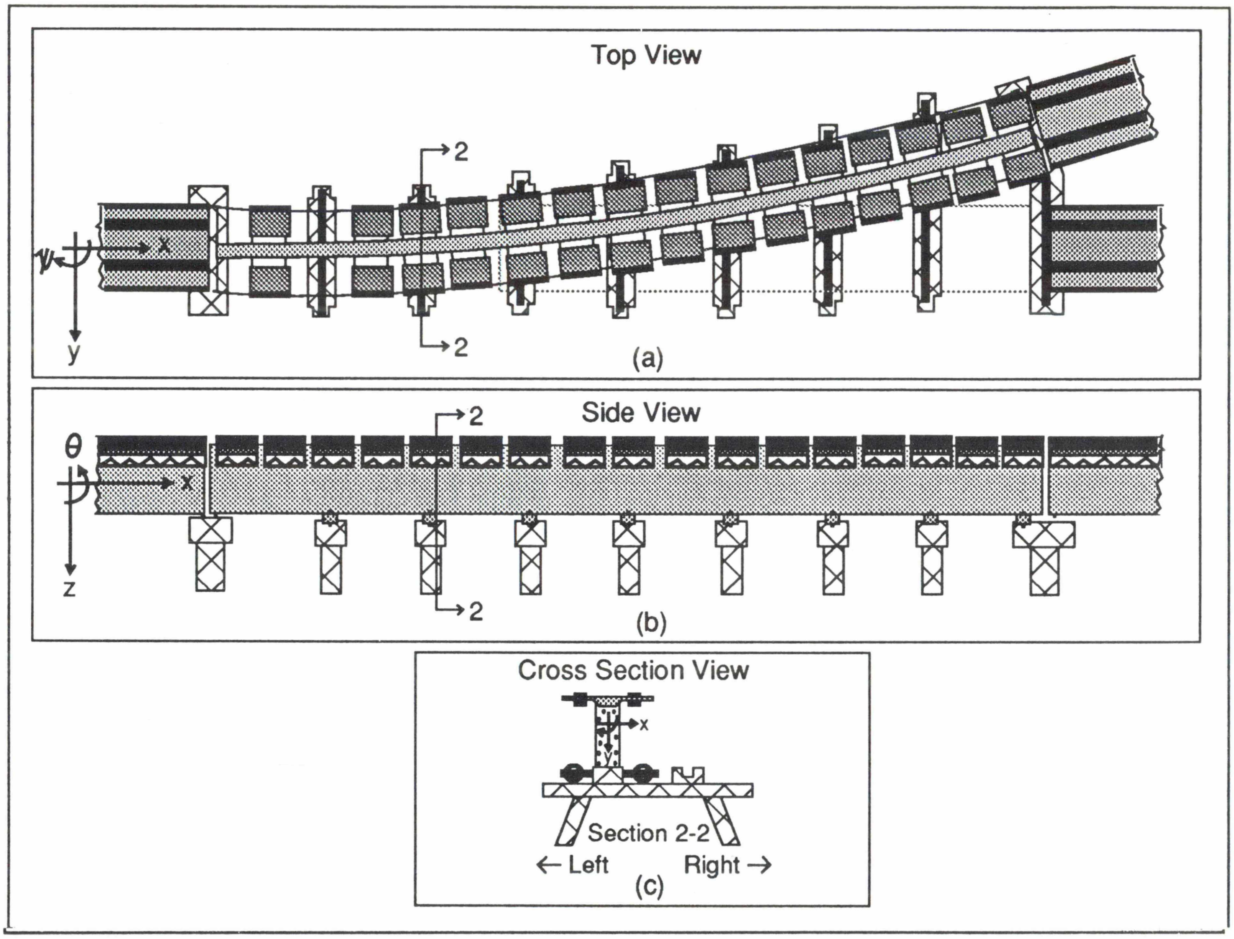


FIGURE 12. HOW SWITCHS BEND TO CHANGE ROUTES

POTENTIAL MAGLEV SAFETY ISSUES

There are four basic methods used to identify hazards. These are:

- Data from accidents (case studies) or operating experience,
- Judgment of knowledgeable individuals and scenario development,
- Generic hazard checklists, and
- Formal hazard analysis techniques.

PREVIOUS ACCIDENTS

Examination of accident experience can provide insight into what has happened in the past. High speed maglev vehicles, although under development for many years, do not have a large passenger service record. The limited operation of high speed maglev systems has not resulted in any deaths or serious injuries. The German pre-prototype Transrapid TR-06 maglev system conducted a public demonstration during June 1988. In twenty-five days of operation, 333 trips were made and 16,650 passengers transported. The system averaged 14.3 trips per day and a total of 96 hours of operation. Only four trips experienced problems and of these four, the vehicle had to be towed back only once. This experience is just too small to provide a full understanding of the hazards that may occur in maglev operations.

EXPERT OPINION AND HAZARD SCENARIOS

The primary safety concern associated with maglev operation is a passenger or employee casualty. Hazard scenarios have been developed to help understand the conditions which may cause these events. These scenarios are often useful to uncover weak links in the safety chain. Judgment by knowledgeable individuals was used to provide a starting point to identify the emergency situations or "undesirable events" which <u>may</u> occur in an elevated guideway maglev transportation system.

The following events (safety issues) represent situations that <u>may</u> produce casualties in any generic elevated guided ground transportation system:

- Fire/explosion in vehicle,
- Fire in other system elements,
- Vehicle collision,
- Vehicle to vehicle collision,
- Vehicle leaves guideway,
- Sudden stop,
- Vehicle does not slow/stop at station,
- Vehicle stranded between stations or safe evacuation points,
- Inability to reach and rescue maglev vehicle occupants, and
- Passenger injury/illness.

GENERIC CHECKLISTS

Generic checklists may be used to identify potential hazards. With this approach, the depth of detail and relevance of the hazard checklist impacts the quality and quantity of hazards identified. As the system design evolves, checklists can provide additional insight into the sources of safety hazards that may be present.

FORMAL ANALYSIS

A number of formal analysis methods are available to identify hazards. Two formal analysis methods are being employed to find maglev system hazards, namely fault tree analysis and preliminary hazard analysis.

Fault Tree Analysis (FTA) charts the relationship between certain specific events and an ultimate result. FTA is a deductive technique which uses the top down approach (what and/or why a particular event happened) to determine the possible causes of an undesired event or system failure.

A review of fault tree diagrams shows that a casualty could occur either in the vehicle, on the guideway or in a station. This is an important point because both severity and the necessary emergency response will vary widely based on location. Certain events which could result in a casualty will occur mainly in the station area. This is particularly true of passenger slips and falls. While such events are less severe, they also occur more frequently. This contrasts sharply with a fire, which may occur in the vehicle at an inaccessible guideway point.

Preliminary Hazard Analysis (PHA) is a technique which can list and logically organize hazards into event trigger categories. The PHA framework defines potential hazards (their nature, types and causes) and recommends possible safeguards and controls. The PHA is an inductive method that uses the bottom up approach (what happens if a specific hazard exists) to determine the effect of a hazardous event or malfunction. A key strength of this analysis is that it provides an expanded, system specific checklist and the opportunity to consider a large number of hazards (some of which, however improbable, could possibly occur). This is important because historical data and experience do not reflect all potential hazards and their effects. A PHA is usually carried out in the early phases of system definition, design and operations planning.

This PHA effort is primarily focused on the identification and resolution of hazards which could result in undesired events.

RISK ASSESSMENT

Once a hazard has been identified, the harm that can result from it has to be estimated. This "harm factor" is known as risk. There are two facets to risk, probability and severity. The chance that a given hazard will actually create a problem can vary greatly. Then, given that a problem exists, how severe is its impact? Risk assessment provides the answer on where to place a hazard on the combined probabilty and severity spectrum. This knowledge can determine if the effort needed to avoid a hazard is justified.

SEVERITY AND PROBABILITY CATEGORIES

Maglev hazards associated with an elevated system have been judged on their chance of occurrence and severity. This provides an indication of which hazards pose the greatest potential threat for casualties and equipment loss. Understanding the nature of the risk will help determine which countermeasures best address the threats. As operating experience is accumulated, the subjective values can be adjusted to reflect severity and probability more realistically.

For this assessment, the expected operating cycle has been defined by the following phases:

- At station.
- Vehicle leaving or arriving at station.
- At inaccessible guideway.
- At accessible guideway evacuation point.

The hazard categories presented in MIL-STD-882B, System Safety Program Requirements, have been modified to assess maglev system event probability and severity. Tables 2 and 3 present these modified categories.

TABLE 2. PROBABILITY CATEGORIES

CATEGORY	LEVEL	EVENT OCCURENCE
A	FREQUENT	Not unusual, could occur ten times annually.
B	PROBABLE	Could occur ten times in maglev system lifetime.
C	OCCASIONAL	Expect to occur at least once in maglev system lifetime.
D	REMOTE	Unlikely to occur during maglev system lifetime.
E	IMPROBABLE	Event is so unlikely that it is not expected to occur.

Event Probability

To establish the probability of an event in absolute terms requires calculation based on previous experience. No such publicly available database exists to derive the probability of an undesired event for passenger carrying maglev systems. Operating experience and data for other mass transit systems exist; however, the availability and level of detail are limited. Thus, the study estimates are subjective and based on the initial fault tree analysis.

Table 4 presents the analysis estimates of undesired event probability. Both the hazard and the inability or failure to control it are required for an undesired event to occur. Thus, for a fire/smoke casualty to occur, a fire/smoke incident must happen with the fire not contained or controlled.

TABLE 3. SEVERITY CATEGORIES

CATEGORY	SEVERITY	CHARACTERISTICS
I	CATASTROPHIC	Death to passenger or employee, loss of maglev system.
II	CRITICAL	Severe injury; hazard or single point failure may lead to catastrophe if control or rescue action is not taken. Critical systems involved and maglev vehicle is unable to move to evacuation area. Response time is important to prevent death or system loss.
III	MARGINAL	Minor injury not requiring hospitalization or the hazard present does not, by itself, threaten maglev system or passenger safety. No critical systems disabled, but could be if additional failure(s), malfunction(s) or hazard(s) occur.
IV	NEGLIGIBLE	Less than minor injury. Does not impair any critical systems.

Event Severity

The severity or impact of event consequences depends on two factors: (1) when the event occurs in the operating cycle; and (2) whether the event is time dependent. For example, the passengers/crew may easily evacuate at a station. In contrast, an emergency on an inaccessible portion of the guideway may not provide sufficient time or capability for escape. When passengers/crew are not able to evacuate, the event will likely result in more severe consequences. Also, the ability to contain adverse effects will affect severity.

RISK ESTIMATES

The risk associated with an undesired event is the product of its probability and the severity of that event. The probability of the undesired events is estimated to be low in most cases. However, the potential severity of some suggests that action may be needed to minimize the risk. A risk assessment matrix can assist the decision making process to determine whether individual hazards should be eliminated, controlled to reduce their occurrence or simply accepted. Table 5 provides this study's risk matrix.

TABLE 4. UNDESIRED EVENT PROBABILITY ESTIMATES

EVENT DESCRIPTION	OPERATIONAL PHASES INVOLVING PASSENGERS			
	Passenger Station Transfer	Leaving/ Arriving Station	Accessible Areas of Guideway	Inaccessible Areas of Guideway
Fire/Explosion in Vehicle	D	D	D	D
Fire in Other Critical Element	C	C	C	C
Vehicle Collision with Object	C	C	C	C
Vehicle to Vehicle Collision	D	D	D	D
Vehicle Leaves Guideway	E	E	E	E
Sudden Stop	N/A	D	D	D
Does Not Slow/Stop at Station	N/A	D	N/A	N/A
Stranded on Guideway	N/A	D	C	C
Inability to Rescue Occupants	D	D	D	C
Passenger Illness/Injury	C	C	C	C

LEGEND:
A Frequent
B Probable
C Occasional
D Remote
E Improbable
N/A Not applicable

TABLE 5. **RISK ASSESSMENT ESTIMATES**

EVENT DESCRIPTION	OPERATIONAL PHASES INVOLVING PASSENGERS			
	Passenger Station Transfer	Leaving/ Arriving Station	Accessible Areas of Guideway	Inaccessible Areas of Guideway
Fire/Explosion in Vehicle	IID	ID	ID	ID
Fire in Other Critical Element	IIIC	IIIC	IIC	IC
Vehicle Collision with Object	IIC	IIC	IC	IC
Vehicle to Vehicle Collision	IID	IID	ID	ID
Vehicle Leaves Guideway	IIE	IIE	IE	IE
Sudden Stop	N/A	IIIC	IIC	IC
Does Not Slow/Stop at Station	N/A	IID	N/A	N/A
Stranded on Guideway	N/A	IID	IIC	IC
Inability to Rescue Occupants	IIID	IID	IID	ID
Passenger Illness/Injury	IIIC	IIC	IIC	IC

LEGEND:

I	Catastrophic	A	Frequent
II	Critical	B	Probable
III	Marginal	C	Occasional
IV	Negligible	D	Remote
		E	Improbable
		N/A	Not applicable

NOTE: IA, IB, IC, IA, IIB, IIIA = Unacceptable;
ID, IIC, IID, IIIB, IIIC = Unacceptable (management decision required);
IE, IIE, IIID, IIIE, IVA, IVB = Acceptable with review by management;
IVC, IVD, IVE = Acceptable without review

RESOLUTION OF MAGLEV SAFETY ISSUES

Methods used to minimize risk are termed "countermeasures." For this study, a countermeasure has been defined as any action or series of actions that may be taken to reduce the casualty risk associated with operation of a maglev system. The risk reduction countermeasure may either eliminate or control the hazard and thereby prevent the event's occurrence or reduce its impact. Prevention of an event is preferable, but not always possible.

Recognizing this, the hazard reduction scheme proposed is the "Design to Eliminate Hazards" approach. This advocates that hazards be eliminated or controlled during system design. If that is not possible, safety devices, warning devices, and/or special procedures and training should be provided. Finally, if none of those countermeasures provide the necessary safety level, a decision must be made to accept the risk or reject the system. Countermeasures that rectify safety issues or hazards can involve: system design, training, operations, maintenance, testing and inspection, configuration management, emergency preparedness, and recertification or reinspection procedures.

DESIGN COUNTERMEASURES

Many countermeasures to address safety issues or hazards may be applied by following existing regulations, standards or guidelines. Other existing safety regulations, guidelines, and requirements adopted by the U.S. government, industry organizations (i.e., FRA, AAR, etc.) and foreign organizations (i.e., EBO, MBO, UIC, etc.) may be applied to maglev systems. These existing codes and standards were developed for railroads (In the U.S.: Title 49 of the Code of Federal Regulations) as well as other transportation systems in the U.S. and Europe. Current FRA regulations, standards and guidelines address many of the subsystems and equipment hazards from the design or performance standpoint.

Redundant or backup systems may be recommended for critical systems and subsystems. Although backup systems are expensive and often complex, such systems are likely to offer the best way to reduce the probability of certain events. However, other methods of hazard control may be more appropriate in some instances. The decision on which systems require backup has to be based on the information available at the time of the analysis.

The following maglev safety issues will be explored further by the FRA and the system developers:

- Maglev vehicle evacuation and access capability.
- Spread of an exterior fire into the occupant compartment.
- Alarms to indicate power loss, air or fluid leakage, or fire/smoke.
- Reaching a safe evacuation area.
- Vehicle crashworthiness and the collision potential with objects and other vehicles on the guideway.
- Automatic activation of emergency lighting upon power loss.
- Protection against battery explosion.
- Redundant ability for communications and vehicle location.
- Validation of fail safe or vital software.

TRAINING COUNTERMEASURES

Training programs should be developed for all safety-related phases of the maglev system operation. Guidelines, which include minimum qualifications for critical positions, should be established. A training path leading to operating personnel certification should be clearly defined, as well as having measurable goals for each aspect of the training. The training guidelines prepared for other rail systems could be adapted for maglev personnel.

OPERATIONAL COUNTERMEASURES

The FRA currently regulates operating rules and practices for railroads. Railroads must file copies of their operating rules, timetables, test and inspections programs, record keeping and drug or alcohol violations with the FRA. Most, if not all, of these regulations apply to the maglev system, but they must be reviewed when the maglev system's operational requirements are further defined.

MAINTENANCE COUNTERMEASURES

Maintenance countermeasures include the development of maintenance procedures and documentation for all safety-related equipment. This includes routine and preventive maintenance procedures and plans. These are usually developed during the design and development phase by the developer and reviewed by the appropriate operating authority and FRA prior to application. Moreover, audits or periodic inspections should be conducted to ensure that approved procedures are followed and preventive maintenance is performed. The maglev vehicles and guideway uniqueness may require existing inspection and maintenance regulations be modified significantly.

TESTING AND INSPECTION COUNTERMEASURES

A testing and acceptance program should be devised to determine if all maglev safety-related systems meet requirements. All test procedures and results of the tests should be documented and provided to the appropriate safety assurance authorities.

CONFIGURATION MANAGEMENT COUNTERMEASURES

A configuration management program should ensure that design, development, and operational changes to safety-related maglev equipment are subjected to strict configuration control and reevaluation testing.

EMERGENCY PREPAREDNESS COUNTERMEASURES

An emergency preparedness plan should be developed to address all aspects of emergency planning and emergency response.

RECERTIFICATION OR REINSPECTION COUNTERMEASURES

As previously indicated, all maglev safety-related equipment needs to be inspected periodically by the appropriate authority. Criteria should be developed to determine what conditions will be cause for reinspection.

DEGRADED OPERATION COUNTERMEASURES

Maglev systems can operate in a degraded mode. Minor malfunctions such as burned-out light bulbs and faulty indicators may not jeopardize the safety of the passengers or crew. However, criteria should be developed to indicate clearly which failures or combinations of failures constitute a minor inconvenience, and which should result in the suspension of system operations.

INITIAL STUDY RESULTS

SUMMARY

- While the maglev transportation system consists of the same basic elements (i.e., facilities, equipment, people, procedures and environment) as any guided ground or rail transportation system, there are several characteristics that are unique to the Transrapid Maglev. Examples are the elevated guideway with wraparound vehicle design, the safe hovering concept, the automatic train operations during emergencies and the procedures to remove disabled trains or vehicles from the guideway. For these reasons, the direct application of most existing railroad regulations will be difficult. However, some regulations do apply to maglev as well as railroads.

- Extensive maglev operational data exist for the TR-06 and TR-07 vehicles at the Transrapid Test Facility, Emsland. However, to determine the scope and magnitude of the maglev safety incidents or accidents likely to be found in revenue service operations requires detailed analysis of this data. Some safety issues may be identified with analysis of additional data.

- The forthcoming TUV Rheinland system operational readiness verification testing, pre-revenue operation, endurance runs on the TVE Test Track and the one year test program of the Florida Maglev Demonstration Project are vital. They must be considered critical to develop the information needed to verify the resolution of the maglev safety issues that have been or may be raised as the system safety study progresses.

- The resolution of safety issues must be confirmed prior to considering revenue service. Some issues identified thus far include fire safety, vehicle crashworthiness, on-board power reliability, suspension failure at high speeds, safe hovering reliability, emergency preparedness (emergency evacuation with wraparound vehicle design, program controlled operations during emergencies, enhanced emergency braking, vehicle evacuation, lightning protection, earthquake impact, etc.), air quality of the passenger cabin during emergency conditions and fail safe guideway switching.

- The FRA will need to modify some existing regulations and develop new ones to address the maglev specific safety issues. A number of German and other transportation industry safety standards/guidelines exist that may be applied to proposed U.S. maglev transportation systems.

- While this preliminary safety analysis has identified ten undesired events and discussed hazard scenarios, the probability of each event is low. However, the projected severity of some requires action to reduce consequences. It is already apparent that action has been taken by those responsible for Transrapid safety in Germany to mitigate known risks.

- More detailed information or analysis is required to evaluate fully the ability of the Transrapid system to perform safely in U.S. applications.

- The Transrapid philosophy to deal with potential safety hazards is to use autonomous, redundant systems in safety critical areas (e. g., control, safe hover, guidance and braking systems). The system is failure tolerant rather than fail safe. This keeps casualty probabilities remote. The FRA can alleviate some safety issues by fostering regulations which deal with the use of failure tolerant designs. The following safety concerns identified at this stage of the maglev safety assessment study relate to failure tolerance:

  - Abuse of Failure Tolerant Design: In a failure tolerant design which depends on two or more redundant systems, it is possible to continue operations even though some part of the redundant systems has failed. There is the danger that the system operator will disregard failures and continue to operate with a system that has lost failure tolerant protection. Operating procedures to address this concern can forbid operations beyond the point where failure tolerance is jeopardized and require failures to be tracked in a protected storage device (e. g., a black box recorder).

  - Emergency Evacuation: Concern exists that passengers cannot exit the TR-07 vehicle safely in any emergency unless the vehicle is at a preestablished exit location. Analysis of the low probability of the vehicle being stranded must be confirmed. This issue could also be alleviated by alternate evacuation techniques.

  - Emergency Brake: The Transrapid vehicle emergency brake system cannot bring the vehicle to an immediate stop in all situations. Continued operation of certain vital automated systems until a stop is achieved is required by this system.

- The ability of the relatively light guideway to withstand the applied forces over time needs further analysis. For example, are single, double or triple spans required to provide acceptable dynamic interaction between vehicles and guideway? Calculations of the applied forces should be reviewed to ensure an adequate design. Conditions such as very high winds, erosion, oxidation, extreme thermal conditions, etc., may affect the guideway structure differently at potential U.S. sites.

FINDINGS

To provide the public with the highest practical level of transportation safety, all critical safety issues associated with maglev transportation must be identified and resolved. The FRA Maglev Safety Assessment Program will suggest the types of countermeasures to resolve them. The developer's first priority should be to select and implement the countermeasures that most effectively eliminate a hazard or safety issue. This initial hazard assessment of the Transrapid system provides early research findings about new rulemaking that should be considered and existing FRA rules and other transportation industry standards that should be modified or adopted. In consideration of alternate approaches to comply with an existing FRA regulations, the "equivalent systems safety" concept may be explored and, where feasible, adopted. Additional safety issues may be identified in further reports as the project progresses.

Existing Rule Modifications

In a number of instances, the safety issues identified in this maglev system analysis are similar to those issues that pertain to existing U.S. rail systems. Recognizing this, the safety regulations applied to the existing rail systems may then be modified for application to the maglev system. In this connection, the concept of "equivalent systems safety" should be a major consideration. The following recommendations address the safety issues identified thus far and the existing regulations, guidelines and standards that may be modified to resolve them:

- The maglev vehicle design should be addressed from the standpoint of structure crashworthiness. The semimonocoque design of the maglev vehicle is similar to that of aircraft and, therefore, not designed to withstand the buff forces that railcars are required to withstand. An in-depth evaluation of the safety requirements for crew/passenger in a high speed crash is essential.

- Existing regulations specify braking requirements for rail cars. In the proposed TR-07 maglev system design, the vehicle brake does not provide immediate emergency braking in all situations (as required in 49 CFR 236.24). Modification needs to be considered to conditionally allow this design, provided it is compatible with the automatic location detection and control system, including train stop.

- The window glazing for the maglev vehicle windshield must reflect the conditions in which it operates. While existing regulations are oriented toward relatively large object impacts, the higher maglev vehicle speed (in excess of 250 mph) introduces windshield vulnerability to impact damage from small objects, like birds. High speed bird impacts may be more analogous to an aircraft than a train. Federal Aviation Administration aircraft glazing requirements (FAR 25.631) need to be considered in modifying existing regulations for the high speed environment.

- Present signal and train control regulations will require extensive modification as noted in "New Rulemaking Initiatives."

- Existing regulations require the submittal of operating rules for approval. Adding a requirement for the submittal of a manufacturing and construction quality assurance plan and an inspection and maintenance program plan should also be considered. Such plans are essential to ensure that improper materials, fabrication, maintenance and operating practices do not degrade the safety design of the maglev system.

- Other areas that may require regulation modification to accommodate maglev transportation are:
  - Electrical safety and electric power supply.
  - Operating personnel qualifications and training.
  - Operating rules and practices.
  - Interior and exterior noise.

Adoption/Modification of Other Rules

In addition to existing FRA and other Federal regulations that can be adopted, modified or created; there are standards and rules which exist or are being developed that may apply to maglev transportation safety in some cases.

- The maglev train safety requirements developed and coordinated by TÜV Rheinland are being reviewed in detail for total or partial adoption into the existing guideline and regulation structure. The results of this review will be contained in the next in a series of reports on the safety of high speed maglev transportation systems. It will be entitled, *Review of German Safety Requirements for the Transrapid System.*

- Passenger car doors are a major cause of injury in mass transit systems. The Transrapid doors are completely different from the doors typically found on intercity railcars. Perhaps the maglev vehicle should have pressure sensitive doors similar to those required in UIC 560.

- EMC/EMI and lightning protection. Electromagnetic interference (EMI) associated with power conditioning equipment can have a disruptive effect on communication control and on board data processing equipment. Existing foreign standards and regulations (DIN and VDE) on EMI and proper methods to measure EMC must be reviewed to establish their application to future maglev systems. The lack of U.S. standards to limit the impact of lightning on maglev safety and operation may require that new standards be developed.

New Rulemaking Initiatives

New rulemaking activities that the Federal Railroad Administration (FRA) will need to consider to minimize the accident potential and the consequences that may occur are contained in the following findings:

- Preparation to effectively respond to an accident requires emergency response planning. Without a plan, the effects of the emergency will not be minimized. For this reason, the FRA should require an emergency plan which addresses systemwide emergency response training and equipment and includes facility emergency preparedness.

- Emergency egress and access to and from the maglev system and the vehicle is vital as accidents and incidents will occur over the lifetime of the system. Provisions must be made to allow passengers and employees to exit the vehicle and allow emergency response personnel access at any location (including on an elevated guideway) where a emergency may occur. At present, with the exception of the requirement for four window exits per car, there are no guidelines, regulations or standards to address this issue.

- In the existing regulations, emergency equipment is only briefly addressed in the form of the need for rear end lights and a handbrake. While this regulation's intent applies, additional rulemaking will need to be considered to address emergency lighting, emergency communications, ventilation (excessive confined air heat buildup from solar heating in Florida and the Southwest), evacuation and the like.

- Fire safety is a major concern as the ability of patrons and employees to exit the maglev vehicle is extremely limited. The existing fire safety guidelines address only flammability and smoke emission characteristics of vehicle interior materials. This is only one element of the fire safety issue. Fire detection and suppression are two additional issues that need to be addressed, since a vehicle fire may develop, spread and result in a major accident if not detected and suppressed. Under conditions of very limited access and egress, the lack of fire detection and suppression systems can result in a minor incident growing into a major fire and thereby result in a catastrophe. Fire safety guidelines also need to address fire containment and fire walls/barriers.

- Elimination or detection of people or objects on the guideway, no matter how remote, is of paramount importance if casualties or collisions on the high speed guideway are to be avoided. Consideration needs to be given to an intrusion detection system or a physical barrier to ensure the security of the guideway, especially in areas where the guideway is easily accessible. This approach will lower the chance of an undetected individual or object being present on the guideway during vehicle operations. Operational and training procedures will also play a major role to reduce the likelihood of trespassers or maintenance personnel being hit by a train.

- Safety verification of the signal and control system is critical in a fully automated transportation system like the Transrapid maglev. Regulations should require positive verification that the control system is fail safe. They should identify the procedure to verify the safety of control systems, including the listing of all vital circuits and the documentation certifying the critical software components. Possible failure modes of the control system should be integrated with the emergency preparedness plans to minimize the potential for injuries and casualties.

- As in the requirements for existing rail operations, there is a need to develop requirements for guideway inspection techniques and criteria to determine the need for maintenance.