SAFETY AND AVAILABILITY OF THE HIGH SPEED TRANSPORTATION SYSTEM TRANSRAPID

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INTRODUCTION

The development of magnetically levitated ground transportation systems was started in 1968 and sponsored by the German Federal Ministry for Research and Technology.

In the first phase of the program (1968 – 1971) a demand and feasibility study was carried out. Alternative techniques for high speed transportation systems were conceived and investigated in detail systematically. As a result it was prognosticated that for specific transportation patterns the establishment of a high speed transportation system would mean a considerable economic advantage. Moreover, the study provided momentum and targets for further development. In the following phase, up to 1978, the development and testing of key components, functional qualification and selection of procedures took place. In this phase the research program covered the whole variety of possible techniques: air cushion technique, permanent magnetic levitation, electrodynamic levitation, electromagnetic levitation.

In December 1977, the Federal Ministry for Research and Technology announced its decision to concentrate its future assistance measures on the electromagnetic system only. Decisive arguments were: low energy consumption, applicability even at low speeds, very low electromagnetic field emission, high cost effectiveness (investment and operational), adaptability to requirements of different applications.

Consequently, the further development program concentrated on electromagnetic levitation and guidance. The final decision on the type of linear motor was made after promising results for low cost production of the guideway–related components of the synchronous iron–cored longstator motor were presented by Thyssen Henschel.

Verification of fail–safe non–contacting operation of the electromagnetic levitation and guidance system has been confirmed by extensive testing of the vehicle TR07 up to speeds of 436 km/h. The TR07, which is a prototype version of the vehicles planned for revenue service, underwent all stages of certification testing at the Transrapid Test Facility in Emsland under independent technical supervision.

State of the art and operating data of the Transrapid were collected and evaluated during two comprehensive studies (1989 – 1991):

- assessment of technical readiness,
- comparative study of hypothetical corridors of application.

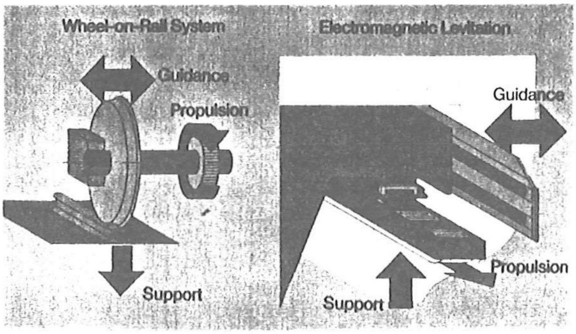
Criteria for the evaluation were in particular function, availability and safety. Further criteria were reliability, operating convenience, flexibility, failure tolerance, maintainability, environmental acceptability, system compatibility, investment cost and comfort. The experts agreed that tests and presented proofs demonstrate that neither system nor safety risks are to be expected. The determination of the readiness for application is the most important prerequisite to include corridors for the Transrapid Maglev System in the latest Federal Transport Infrastructure Plan in Germany.

1. SYSTEM DESCRIPTION

1.1. Technology

The number and kinds of technologies, interfaces and transformation processes determine the complexity and potential of high speed transportation systems especially with respect to availability, safety and economic feasibility. The characteristics of the synchronous iron–cored longstator motor are ideally suited for the requirements of a tracked high speed transportation system. Through consistent use of these characteristics the Transrapid can perform the basic functions of levitation and guidance, acceleration and braking exclusively through electromagnetic forces without intermediate mechanical, hydraulic or pneumatic conversions.

Figure 1



Comparison of Systems Railroad/Maglev

State of the art of electric components such as magnets, stator pack and motor windings and the application of modern power electronics and microelectronics for automatic control, diagnosis and maintenance results in a system design of high operational performance, especially with respect to availability, safety and ease of handling.

1.2. Technical Concept

1.2.1. Propulsion

The linear longstator motor comprises stator packs with a three–phase winding installed under the guideway (comparable to the stator of a rotating motor) and electromagnets provided on the entire length of the vehicle (corresponding to the rotor of the rotating motor). The "guideway motor" is divided into sections which are individually activated by the appropriate substations as the vehicle enters the respective section. Acceleration and braking capability, which vary locally due to routing and operational requirements, can be accommodated easily by varying the length of the motor sections, diameter and/or conductivity of motor windings and feeding cables, power and distance of substations. These characteristics demonstrate the outstanding suitability of the synchronous iron–cored longstator motor for tracked high speed transportation.

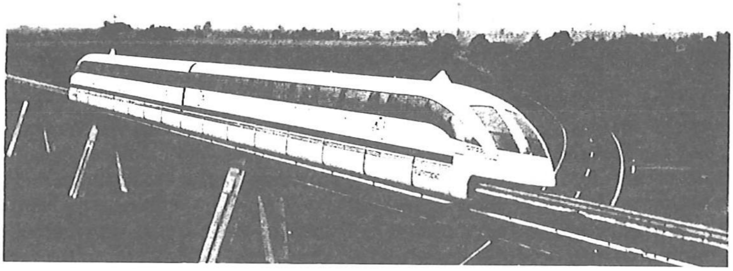
1.2.2. Guideway

Various types of guideway structures will be considered during route planning with regard to cost efficiency and environmental aspects:

- single– or double–track guideways with steel or pre–stressed concrete beams on piers of up to 20 meters high,
- at–grade guideway for tunnels, cuttings, bridges and areas wherever this is required for better general acceptance.

In order to change track an appropriately designed steel beam is elastically bent by means of electromechanical actuators. Switches for maximum vehicle transversing speeds of 100 km/h and 200 km/h in the bending branch have been developed and tested.

Figure 2



TRANSRAPID 07

1.2.3. Vehicles

Transrapid vehicles are designed to cruise at speeds of 300 to 500 km/h and to transport passengers or express goods. If it is convenient, passenger and container units can be combined to form mixed train sets of up to ten units.

Flux–coupled electromagnets arranged in a redundant configuration and controlled in two degrees of freedom are used to levitate and guide the vehicle on the guideway. Dynamic stability and a sufficient air gap for non–contacting operation even in case of component failures are ensured by autonomous fail–safe electronic gap control systems.

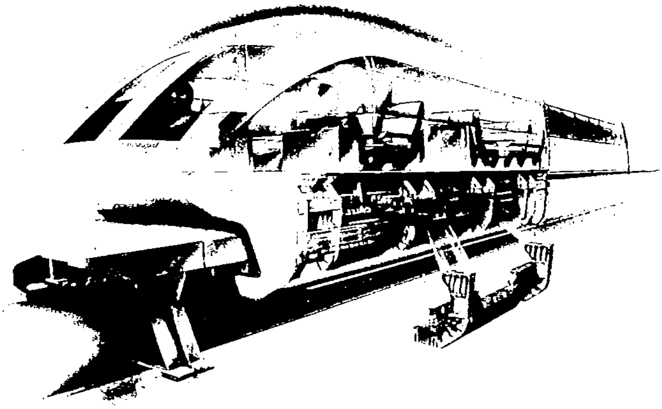
Safe–life power supply of the vehicles is provided by linear generators independent of any external power supply. These generators, integrated in the poles of the levitation magnets, convert part of the vehicles' kinetic energy into electrical energy. Safe–life behavior is achieved through adequately high redundancy. At low speed the on–board power supply network is buffered by batteries.

Safe–life braking function is assured by modularly designed eddy–current brakes.

Skids settle on the guideway to support and stop the vehicle when it comes to a standstill and the electromagnetic levitation system is deactivated.

Structure and design of the cabin is comparable to modern railway coaches. Air conditioning and interior furnishings meet the respective aviation standards.

Figure 3



TRANSRAPID 07 Levitation and Guidance Module

1.2.4. Automatic Train Control

The signal and control system is designed to ensure safe train operation. It serves two basic functions: providing a safe unobstructed travel path (route integrity) and maintaining vehicle speed with designated operating specifications (safe speed enforcement). The system relies mainly on microprocessors which are designed, and their operation verified, with fail–safe, fail–active, and fail–tolerant methodologies for hardware and software.

1.3. Technical Data and Performance

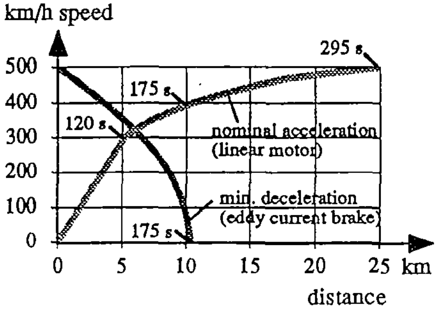
The technical data and performance characteristics given in the following table and figures 4, 5, 6, 7, 8 are derived from simulation results and/or evaluation of measurements of test rides at the Transrapid Test Facility in Emsland.

Table 1.

Max speed	400 to 500 km/h	Useable area per car 78 m^2	
Max gradient	10 %	Seats per unit	56 to 113
Train sets	2 to 10 units	Tare weight Passenger unit Goods transport	 46.000 kg 42.000 kg
Total length Nose unit Middle unit	 26.990 mm 24.770 mm	Total weight Nose unit Middle unit	 55.000 kg 58.500 kg
Max width	3.700 mm		
Energy consumption per m^2 of useable area and km			38 to 45 Wh/m^2km

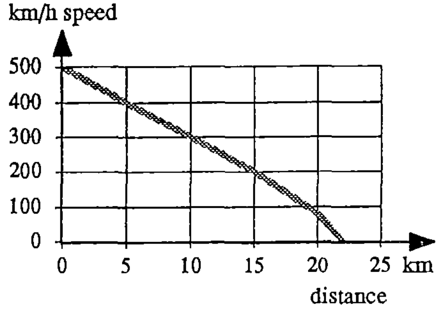
Technical Data of the TRANSRAPID System for Revenue Service

Figure 4



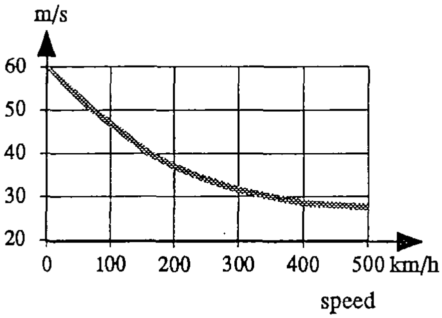
Acceleration and Braking Ability

Figure 5



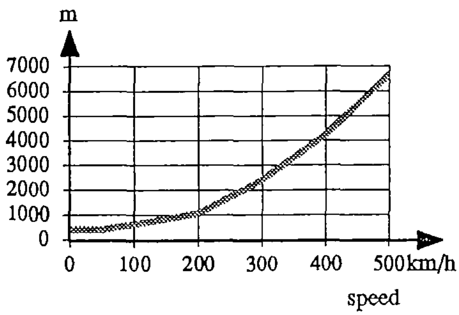
Coasting Ability (Worst–case)

Figure 6



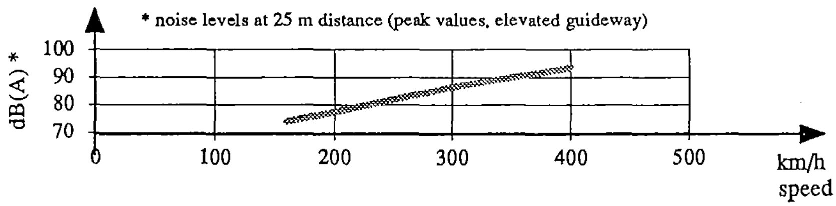
Crosswind Compatibility

Figure 7



Minimum Curve Radii

Figure 8



Noise Measurements of the Prototype Vehicle TR07
(Ref.: TÜV–Rheinland and others)

2. SAFETY ANALYSIS

The Transrapid high speed transportation system has been subjected to a detailed and comprehensive safety analysis and evaluation.

Methodology and procedures applied rely on developed and verified techniques. The aim of the study was the elaboration of a safety concept taking into account both the system's technical characteristics and operational parameters as well as its environment.

In order to assess the safety the following questions have to be answered:

What can happen? What may not happen?

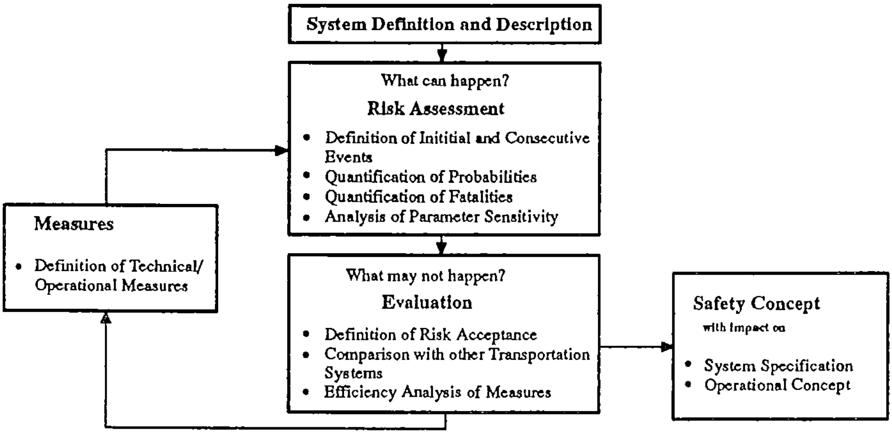
In the evaluation process all forms of injury to persons are represented by a probable number of fatalities. The definition of the most effective measures to increase and maintain safety was the dominant part of the work packages.

2.1. Outline of Hazard Assessment

The objectives of the safety analysis require a quantification of risk to allow
- identification of safety–relevant weak points,
- consideration of rare events (for example earthquake),
- definition of safety measures with optimum efficiency,
- comparison with known risk of operating conventional transportation systems.

The criterion of the evaluation is injury to any individual, inside or outside a train, caused by technical, environmental or human influence. Effects of sabotage and vandalism are not considered. The first step of the analysis is to closely describe the system including the operational and environmental conditions. In the next step, the analysis detects initial and consecutive events, which may result in a final event of injury to any individual. On the basis of a defined, quantitative criterion to decide acceptance or refusal of risk, safety measures have been defined and evaluated in a closed loop processing of risk assessment and evaluation. The end of the iterative process results in a final safety concept (Figure 9).

Figure 9



TRANSRAPID Safety Analysis – Methodology

2.2. Methodology of Risk Assessment

2.2.1. Master Diagram

All initial and consecutive events resulting in risk of fatality are systematically arranged in master diagrams, considering injury to individuals inside the train, outside the train, and at ingress/egress respectively. Basic groups of consecutive events are interior impacts such as fire in train, exterior impacts such as explosion outside the train and collision with another train, unexpected obstacle, and deformed guideway.

In order to take all primary events into account in addition to known events in conventional systems, a detailed project–specific analysis has been carried out, in accordance with the environmental situation of the system with its landscape, climate, urban or industrial structure and the probability and intensity of earthquakes.

2.2.2. Fault Tree Analysis and Input Data Evaluation

For quantification of risk, the determination of the probabilities of every single initial or consecutive event in the master diagram is required.

The Fault Tree Analysis is an approved method to quantify the probability of any undesired top event defined in the master diagrams. Basic elements of fault tree processing are

- mathematical algorithms according to standards,
- system description by fault tree structure with verification of system failure behavior by respective bench tests and at the Transrapid Test Facility in Emsland,
- verified Mean Time Between Failure (MTBF) of the components.

In order to determine the required quantities, history record data of every type of subsystem and component are subjected to statistical evaluation under consideration of operating conditions and standards.

2.2.3. Event Tree Analysis and Estimation of Fatalities

The Event Tree Analysis represents a procedure of scenarii, resulting from a consecutive event of given probability. It indicates how an event may branch into different subsequent events and situations. Each end of the branch defining a possible final state of the initial event is weighted by the probable number of fatalities. For a reasonable simplification of estimation, categories with a standardized number of fatalities are defined.

The entire quantification process starts with a consecutive event with a probability P determined by fault tree analysis. The event tree describes the possible scenarii resulting from this consecutive event where every branch is given by a probability X. The fatality category to be applied for each branch depends on operational conditions, for example speed of the train. It results from medical expertises dealing with the impact of fire or shocks of acceleration caused by collisions.

2.2.4. Efficiency Analysis of Measures

With the procedure of analysis described, an objective evaluation of the efficiency of different safety measures can be performed. Any investigated safety measure can be assessed by the resulting decrease of fatalities. As a result of the procedure, a bundle of safety measures for the Transrapid system was defined and confirmed as to be highly efficient.

Measures defined for an investigated application project may vary if other application conditions are considered. Therefore, an extended catalogue of additional measures has been worked out.

2.3 Safety Features

As a new transportation system the Transrapid profits from experiences made with existing systems by avoiding from the outset known accident risks. On the basis of statistical data eight basic types of accident encountered in road and rail traffic have been identified (table 2).

Table 2

Location	Type of accident No. Description	Persons involved
INSIDE the vehicle	1 Collision with another vehicle of the same traffic system 2 Leaving the track 3 Collision with vehicle of different system 4 Collision with unexpected obstacles	Passengers and staff (= drivers for road traffic)
OUTSIDE the vehicle	5 Crossing the track in vehicle of different system 6 Crossing the track on foot	Third parties
When getting on and off	7 Jumping on and off a vehicle in motion	Passengers
Inside or out-side the vehicle	8 Other types of accident: falling onto track, being hit by vehicle, fire in vehicle	Passengers, staff, third parties

Types of Accident

Applying the methodology described, safety measures and resulting system requirements were defined and taken into consideration during development and qualification.

The most important safety–relevant characteristics of the Transrapid system are:

- Absence of level crossings.
- Dimensioning and qualification of guideway structure and mounting bolts according to safe–life standards.
- Redundant fastening of stator packs and on–line monitoring by cruising trains.
- Exclusion of the possibility of derailment since the suspension system wraps around the guideway.
- Realization of safe hovering and on–board energy supply by redundant, autonomous and modular subsystems and components designed with fault tolerant techniques.
- Achievement of safe braking by a safe–life eddy–current brake on board the vehicle.
- Fire protection of the train (civil aviation standards).
- Automatic train control to maintain safe enforcement and route integrity.
- Exclusion of human failure reactions by fail–safe interlocking and automatic operation.
- Control of maximum and minimum speed to ensure sufficient kinetic energy of train to reach the next stopping place.
- Protection of passengers at ingress and egress of train by a gate system.

Concerning the overall system safety evaluation, it is important to note that the risk contribution by failures of technical subsystems are negligible compared with risk induced by non–technical (environmental) impacts.

The most prominent features of the Transrapid, namely its elevated guideway and the high speeds, raise two questions:

- Where and how can people be evacuated from the vehicle in case of an emergency?
- What are the effects of a collision with a guideway element or with an unexpected obstacle?

2.3.1. Rescue Strategy

The safe hovering concept ensures that the vehicle comes to a stop only at locations where auxiliary power and evacuation are provided. Such places are stations and additional stop locations. The distances are designed so that in case of an emergency the vehicles can reliably coast, even in the presence of worst–case situations.

This rescue strategy ensures that the passengers can leave the vehicle in an emergency at a suitable, i.e. protected location, until their onward transport is organized.

Additional provisions have been made for the most unlikely event that the vehicle comes to a stop between stop locations. The respective means for evacuation are on board and/or installed guideway–side. Their choice depends on the local requirements.

2.3.2. Collisions

To avoid collision between vehicle and guideway or large massive obstacles, the following measures are taken:

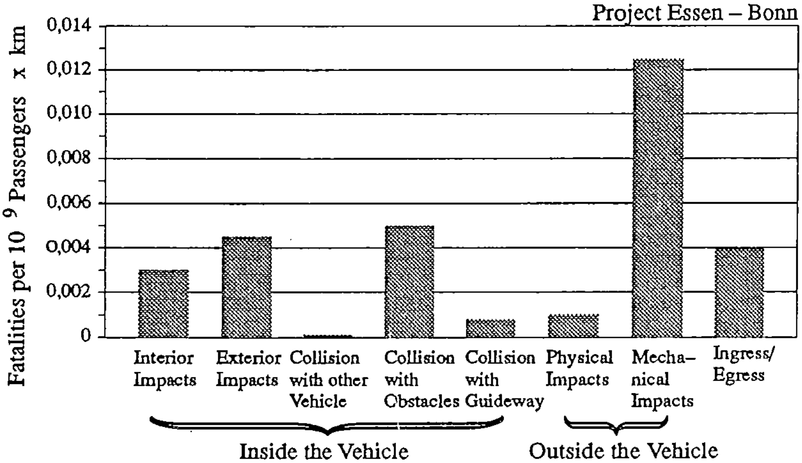
- The method of construction of the guideway excludes the possibility of large deformations. In this respect, both the local conditions and a possible earthquake loading are considered.
- Guideway structure and mounting bolts are dimensioned and qualified according to safe–life standards. Stator packs are mounted with additional redundant bolts and are monitored on–line by every cruising train.
- Piers and beams of the guideway at underpasses are collision–protected.
- In case of overhead traffic constructional measures have to prevent vehicles and objects from falling onto the guideway.
- Organizational and operational measures as care of trees in wooded sections, operation restrictions during periods of extremely bad weather.

Furthermore, the vehicles' behavior even for improbable cases of collision with guideway equipment (stator packs) or obstacles of various sizes and weight are being investigated in detail using the latest state of simulation techniques to analyze collision resistance and crash worthiness with respect to acceleration levels in the cabins and impact on structure and components of the train. The results obtained up to now show that due to the specific characteristics of the levitation bogies, the elasticity and damping of the coupling and last but not least due to the impossibility of derailment comparativly low g–forces experienced by the passengers and less damage to the vehicles are to be expected.

2.4. Results

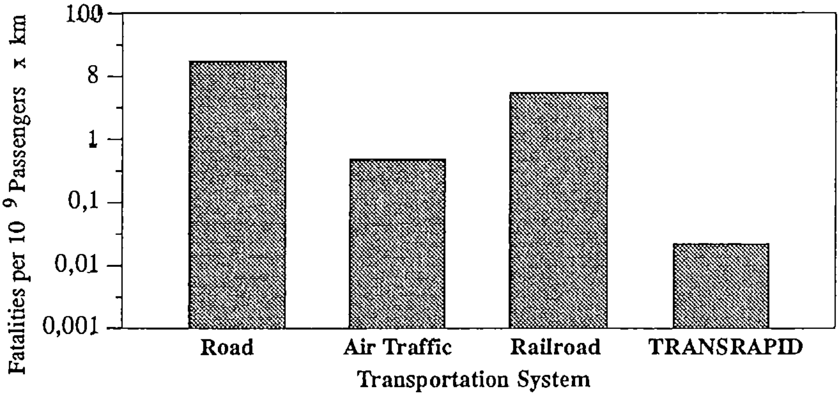
Figure 10 indicates the probability of fatalities per passenger km. The numbers in Figure 10 become much more expressive by comparison with the statistically well–known numbers of fatalities occurring at other transportation systems given in Figure 11.

Figure 10



TRANSRAPID Safety Analysis – Fatalities

Figure 11



TRANSRAPID Safety Analysis – Comparison of System Risks

Evaluating the difference between conventional railroad and Transrapid, it has to be taken into account that the Transrapid system, as a new designed system, profits from experience of existing systems, applying the state of the art in its subsystems. Most benefits result from automatic train control and safe–guarding of operations, exclusion of level crossings, installation of station platform gates, and state of the art measures for active and passive fire protection. The efficiency of most of these measures for risk reduction has been clearly proved by operational experience with modem railway systems.

Because of the exclusive characteristics such as
- complete functional redundancy of levitation, guidance, propulsion and braking,
- on–board power supply relying on kinetic energy of the train,
- only low voltage equipment on board,
- safe hovering combined with automatic train control for emergency evacuation exclusively at predefined locations with easy access and egress and suitable environment for passengers,
- exclusion of derailment,

the Transrapid system has the potential to reach the highest safety level.

3. AVAILABILITY

High availability of subsystems is important to ensure that the Transrapid system maintains a high level of operating efficiency in revenue service.

This is achieved through:
- Error–tolerant behavior, i.e. mission accomplishment even in case of several component failures.
- On–line diagnosis.
- Automatic deactivation in case of failure and on–line self–check including reactivation routines.
- Computer–aided equipment for preventive and corrective maintenance.
- Insensitivity to environmental influences (outside temperature, wintry conditions, lightning, crosswind).

A component diagnosing failure is automatically deactivated and separated from the power supply to limit the effect on the system function. This enables the safe prognosis of the consequences by fault tree analysis. If tolerable with regard to safety requirements, several reactivation trials – also automatic – occur after the automatic shutdown during operation. A reduction of the system availability by fault diagnosis respectively by short–time functional disturbances can thereby be avoided to a high degree. Shutdown and reactivation cycles are registered during operation by diagnosis in order to ensure consideration of the intermittent component failures in the maintenance procedure.

The high redundancy combined with monitoring and control to achieve safe–life operation of levitation, guidance and braking ensures very high availability of these functions.

Adequate availability of the propulsion system is achieved by applying modular, decentralized structured diagnosis and control techniques ensuring that the functional redundancy described under para. 1.2.1. can be used efficiently in revenue service.

Although the operational control system required to maintain safety, control and effective supervision of operation has a modular decentralized structure. To achieve fault–tolerant operation and high availability full redundancy is applied. The automatic train control system relies on various microprocessors. The SIMIS (Siemens Corp.) based hardware is operated successfully in signalling and control systems of interlocking installations and train control systems in revenue service of modern railway systems. The features and especially the high reliability have been approved by the German Federal Railway (DB).

Development and optimization of effective maintenance procedures are a very important part of further system optimization. Development models of computer–aided equipment to ensure economic procedures for preventive and corrective maintenance on a high quality level are installed in the Transrapid Test Facility and undergo continuous testing in daily operation. Periodic reviews of the procedures applied enable the determination of specific changes for improvement of completeness and simplification of handling.

Insensitivity to environmental influences is achieved by the contactless function with sufficient air gap reserve combined with the protected arrangement of guideway components (stator underneath, vertical guidance rail) with respect to wintry conditions. Electromagnetic compatibility and lightning protection have been proven by worst–case qualification testing including shock currents up to 63 kA. The active guidance system is dimensioned to accommodate the specified loads generated by crosswind, aerodynamic pressure waves and free horizontal acceleration.

CONCLUSIONS

After successful demonstration of the outstanding technical features of electromagnetic levitated high speed transportation systems, the activities were concentrated on safety and availability as dominant factors to be resolved prior to revenue service.

The aim of the safety investigations was the elaboration of a safety concept based on the comprehensive description and analysis of all safety–relevant factors. Measures to increase safety were defined and their effectiveness investigated.

Availability has been analyzed describing the failure behavior by a detailed fault structure, estimation of mean time between failures, definition of operational measures and development of maintenance procedures. For verification of essential data and characteristics respective theoretical analysis and verification by endurance tests have been carried out.

The results obtained clearly verify that high levels of safety and availability can be expected in revenue service of the Transrapid system.

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