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Maglev Guideway and Route Integrity Requirements

Final Interim Risk Identification Report

U.S. Department of Transportation

Federal Railroad Administration

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Air Traffic Systems

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FOREWORD

Martin Marietta Corporation, Air Traffic Systems, submits this Final Interim Report to the Federal Railroad Administration (FRA) as required under Contract No. DTFR53-91-C-00067, Maglev Guideway and Route Integrity Requirements.

CONTENTS

1.0 SUMMARY (ABSTRACT)

Transportation specialists have pointed to the inherent advantages of magnetic levitation (maglev) system architectures that include dedicated guideway which precludes many potential collision hazards (reference 26). Use of a synchronous motor has been cited as contributing to reduced risk of two trains colliding (reference 23). These observations and others have been shown to be oversimplifications through studies performed by Transrapid International (reference 28); TUV Rhineland (reference 27); and the U.S. Department of Transportation, Federal Railroad Administration (References 3,4), and is corroborated by this study. While some potential maglev architectures contain features of inherent safety and high reliability, risks associated with high-speed ground transportation have potentially serious consequences, and therefore require careful consideration, analysis, and effective mitigation.

This report documents the risks accompanying the potential hazards encountered by a maglev system. Risk mitigation is not presented as part of these findings. The hazards identified, and their associated risk assessments, are useful as a foundation for risk mitigation strategy definition and will support analyses during the early phases of system development. The report can assist the development of system safety requirements and the preparation of performance and design specifications.

The maglev system is in the concept exploration phase and little is known about the system architecture and component design. A few assumptions were made as to the characteristics of the maglev system to better inform the engineering judgment used to identify hazards and assess the associated probability of occurrence and severity of consequences. The approach taken to risk identification and assessment is based on a preliminary hazard analysis (PHA), as described by MIL-STD-882B, Systems Safety Program Requirements. The categories selected for severity, probability, and risk are similar to those suggested by the standard, and complementary to those used in recent FRA studies.

Hazard probability and severity characterizations are based on a physical architecture and operations concept which pre-supposes good standard design practices, but no special mitigation techniques. An example is that the consist is assumed to be constructed to withstand impact with lightweight objects, but the guideway is presumed to be fully unshielded, permitting hurled objects to land on the guideway. Other key assumptions include: 90% or more of the guideway is elevated 3m or more above ground; maximum speed of 134 m/s; 40-year nominal system life;

operational procedures roughly analogous to Transrapid; and no particular geographical location is assumed.

Current and historical literature was reviewed to assist the determination of maglev hazards and their associated severity and probability. Appendix A lists maglev, high-speed rail, conventional rail, and risk assessment literature which was reviewed to provide insight into the hazards which may affect maglev systems. Forty-eight hazards were identified and separated into four categories:

1) Obstruction and Fouling;
2) Guideway Integrity;
3) Physical Security hazards;
4) Other hazards.

Potential hazards were evaluated and assigned to one of four levels of severity (catastrophic, critical, marginal, and negligible) and one of five probability categories (frequent, probable, occasional, remote, and improbable). Definitions of these terms are included in Appendix B. Continued review and substantiation of hazard characterizations is appropriate as a specific system design emerges.

Very few of the risks are truly unique to maglev. The primary new risk introduced by maglev is due to the very high speed operation at, or near, ground-level coupled with lightweight construction. Of the 48 risks identified, 38 are characterized as unacceptable and must be mitigated prior to system deployment. The high number of risks characterized as unacceptable is a result of the conservative methodology used which assigns an "unacceptable" risk to any hazard that may result in even a single death, and a result of the absence of mitigating system features from this analysis. Two-thirds (25) of the unacceptable risks, such as heavy objects on the guideway, trespassers, and fires, were judged as catastrophic in severity for potentially causing a human death. The other 13 unacceptable risks, such as extreme weather, guideway distortions, and station crime, were judged of sufficiently frequent probability of occurrence that mitigation measures are warranted. The remaining 10 risks, such as small rocks and animals on the guideway, are characterized as requiring judgment by the project management (operators, developers, and financiers) as to acceptability.

Continued review and substantiation of hazard characterizations will be a part of ongoing safety analyses. Some residual risk will remain after the best attempts at mitigation through proper design, passive techniques, sensors, and mitigation through operational procedures. This residual risk must be judged acceptable for the system to reach the deployment stage. The risks identified in this report may be applied to any maglev systems concept, design, or implementation for assessment of appropriate risk mitigation measures.

This risk identification task is the first of three tasks in this study effort. The findings of this risk identification task will provide a foundation for the subsequent tasks. The second task will evaluate sensor-based systems as a potential risk mitigation strategy. Although sensors are specifically analyzed in that task, this risk identification serves as a point of departure in assessing other mitigation strategies as well. The final task of this study will identify a conceptual communications architecture to connect the preferred sensor monitoring system with vehicle and wayside control system elements.

2.0 TASKS PERFORMED

This interim report on the Maglev Guideway and Route Integrity Requirements study Risk Identification task is provided under Paragraph 4.1.7 of the statement of work (SOW): "Prepare draft and final interim reports that profile identified risks." Table 2-1 shows the SOW requirements and the location of the report sections which fulfill those requirements.

Table 2-1 Reference to SOW Requirements and Location of Response

SOW Requirement	**Paragraph Reference**
a. "4.1.1 Characterize the obstruction or fouling of a vehicle guideway or operational envelope;"	Paragraph 3.3.1.
b. "4.1.2 Identify potential obstructions, determine the source of those obstructions, assess the consequence of each obstruction, assess the probability of occurrence associated with each obstruction, and develop a risk profile for identified obstructions"	Paragraph 3.3.1.
c. "4.1.3 Characterize loss of integrity of vehicle guideway;"	Paragraph 3.3.2.
d. "4.1.4 Identify potential causes of guideway misalignment/disruption, describe associated manifestations, assess the probability of occurrence, assess the consequence of occurrence, and develop a risk profile for each identified potential cause;".	Paragraph 3.3.2.
e. "4.1.5 Identify physical security hazards and characteristic risks;"	Paragraph 3.3.3.
f. "4.1.6 Identify other hazards such as vandalism and characteristic risks;"	Paragraph 3.3.4.

3.0 FINDINGS

3.1 INTRODUCTION

The Maglev Guideway and Route Integrity Requirements study contract is divided into three distinct tasks. Figure 3-1 shows the relationship of these tasks and itemizes the corresponding outputs of each task. The findings of the Risk Identification task reported below provide a foundation for the subsequent tasks. The Technology Assessment task will evaluate sensors for those risks which are most amenable to mitigation by cost-effective sensor-based systems. The Communications Assessment task will result in the identification of a conceptual communications architecture to connect the preferred sensor monitoring system with vehicle and wayside control system elements. Separate reports will discuss the results of the latter tasks.

This Interim Report on Risk Identification documents the estimates of risk accompanying the potential hazards encountered by a maglev system. The report will support systems analyses during the early phases of system development. Although the current contract effort will continue with an analysis of sensor-based solutions, the findings reported below will be generally useful as a foundation for the assessment of other mitigation strategies. The report can be used to assist the development of system safety requirements, and in the preparation of performance and design specifications. Finally, this study can be extended and refined as the system design concept evolves and a detailed system design emerges.

The findings of this Risk Identification task are reported in the two following sections. In section 3.2, the approach taken to identify risk is described. This description includes an explanation of the underlying methodology tailored from MIL-STD-882B, System Safety Program Requirements (reference 1). whereby hazard categories are selected and assigned probability and severity ratings to estimate risk. Assumptions made about the characteristics of the maglev system used in this analysis are also described.

In section 3.3, the specific risks are identified for many distinct hazards. The hazards are organized in four categories: Obstruction and Fouling (3.3.1), Guideway Integrity (3.3.2), Physical Security (3.3.3), and "Other" (3.3.4). Tables are provided in these sections which list each hazard by hazard category and identify the associated probability, severity, and risk.

References and definitions may be found in Appendixes A, and B respectively.

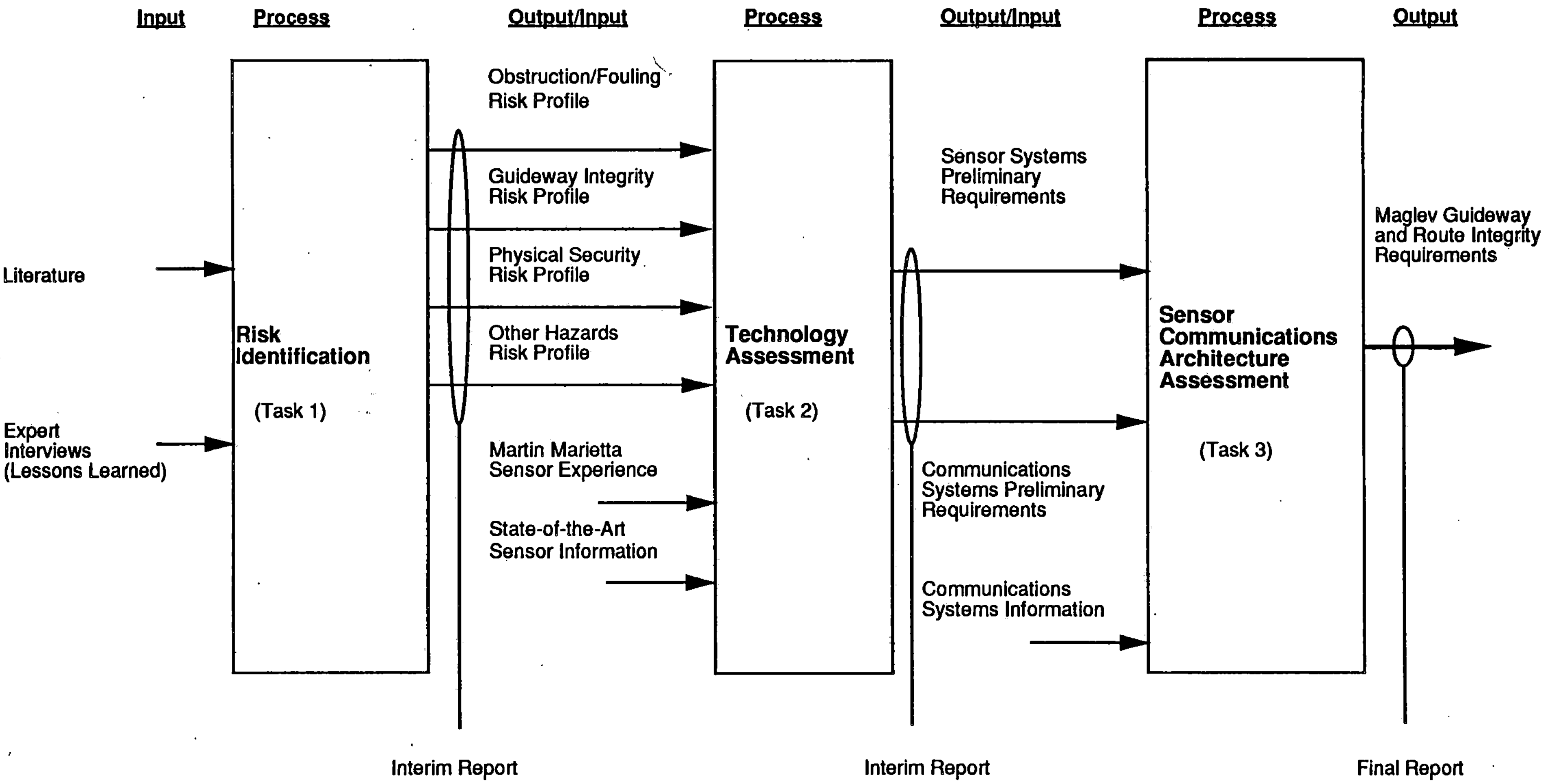

Figure 3-1 Relationship between the Three Tasks of This Contract

3.2 APPROACH

3.2.1 Methodology

MIL-STD-882B was used to guide this work. MIL-STD-882B outlines a program for system safety of which portions are shown in Figure 3.2.1-1. The content of tasks, plans, and reviews will necessarily vary depending on the phase of the system life-cycle. Appendix B of the standard, for example, is entitled System Safety Program Requirements Related to Life-Cycle Phases.

Maglev is currently in the concept exploration or concept selection phase which is highlighted in Figure 3.2.1-1. For the purpose of this risk identification analysis, no particular system concept was assumed (see paragraph 3.2.5). The levels of detail and the estimates in these early phases reflect the fact that only early notions of the final system design are available. Our approach to risk identification is to perform a PHA, as described by the military standard. At each system life-cycle stage, the hazard analysis is used to recognize those hazards which must be managed. Resources can be focused appropriately on the hazards having the highest risk and most severity.

The initial PHA is typically performed during system concept exploration. During the concept exploration phase the system concept is not well formed, not all risks can be identified or accurately assessed, and appropriate mitigation strategies are not yet clear. The initial PHA serves as an indication of the system risks which should be addressed in the maglev design phase. As more information about the system design is known, the PHA can be extended and refined. These safety analysis iterations serve as a basis to evaluate design options from a safety perspective and uncover increasingly more subtle hazards and corresponding consequences to the maglev system. Figure 3.2.1-1 shows a portion of the safety analysis progression as the maglev system matures through the life-cycle phases.

MIL-STD-882B recommends the mitigation of hazards through design. In the concept exploration phase, hazard probability receives less emphasis than it will receive in later development cycle phases, after it has been determined which hazards are not readily mitigated by vehicle/guideway design. Initially, system designers concentrate on the elimination of the most severe hazards, independent of the hazard frequency. The hazards which remain unacceptably risky can be examined with emphasis on reducing the highest risk hazards.

Life Cycle* \ Selected 882B Tasks	System Safety Program (SSP)	System Safety Program Plan (SSPP)	Hazard Tracking & Risk Resolution	Preliminary Hazard Assessment (PHA)	Subsystem Hazard Analysis (SHA)	Software Requirements Hazard Analysis (SRHA)
Concept Exploration	X	X		⊗		
Concept Selection	X	X		X		
Demonstration Validation	X	X	X	X	X	X
Full-Scale Development	X	X	X	X	X	X
Production	X	X	X	Changes Only	Changes Only	Changes Only
Deployment Initial Operating Capability						
Operation and Support						
Disposal						

*Life-cycle phases are drawn from Reference 2, Systems Engineering Management Guide.

Figure 3.2.1-1 Mil-STD-882B, System Safety Program Requirements (Small Sample Only -- 882B is Help Plan -- Not Mandated List of Tasks)

3.2.2 Probability, Severity, and Risk

Suggested probability, severity, and risk categories are provided in Appendix A of MIL-STD-882B. However, these categories have been modified in previous FRA-sponsored work (References 3,4), a procedure which is encouraged by the military standard. We have re-used these modified probability, severity, and risk categories. Table 3.2.2-1 defines these modified categories as they are used in this study. System loss is defined here as the loss of use of the maglev system or a system route, due to an accident, for one or more days. This loss may be due to guideway damage or malfunction, broken and unmovable trains, or other causes. A value of risk is assigned to a given hazard for each combination of severity and probability values. The relationships between these parameters are shown in Table 3.2.2-2.

The risk and severity categories are used to prioritize the hazards for corrective action. Risk is quantified in this manner to enable managing authorities to "properly understand the amount of risk involved relative to what it will cost in schedule and dollars to reduce that risk to an acceptable level." (MIL-STD-882B, paragraph 30.3.1)

It was assumed that "good" conventional design, or better, would be applied throughout the system. Engineering judgment was then applied to assess probability and severity for each hazard. The MIL-STD-882B recognizes that it may be difficult to assign quantitative values at this phase of system design. "...Assigning a quantitative hazard probability to a potential design or procedural hazard is generally not possible early in the design process." (MIL-STD-882B, paragraph 4.5.2)

3.2.3 Information Gathering Approach

Literature on the safety aspects of maglev, high-speed rail, and conventional railroads was reviewed. Background literature on potential maglev vehicle/guideway designs, and on risk assessment, was reviewed to better understand the context of the hazard analysis and risk identification.

3.2.4 Risk Mitigation

Risk mitigation is not presented as part of these findings. Mitigation achievable through sensor-based systems will be analyzed as part of the Technology Assessment task in this study. Mitigation through other means can be addressed using the risk identification findings reported in section 3.3.

Table 3.2.2-1 Probability and Severity Categories

Probability Categories

Frequent -	Not unusual, could occur ten times annually.
Probable -	Could occur ten times in maglev system lifetime
Occasional-	Expect to occur at least once in maglev system lifetime
Remote-	Unlikely to occur during maglev system lifetime
Improbable-	Event is so unlikely that it is not expected to occur.

Severity Categories

Catastrophic-	Death to individual, loss of maglev system
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
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 failures, malfunctions, or hazards occur.
Negligible-	Less than minor injury. Does not impair any critical systems.

Categories are based on MIL-STD-882B, Appendix A; See text concerning modifications.

Table 3.2.2-2 Risk Assessment Based on Severity and Probability

Probability	**Severity**			
	Catastrophic	**Critical**	**Marginal**	**Negligible**
Frequent	Unacceptable	Unacceptable	Unacceptable	Acceptable with Review by Management
Probable	Unacceptable	Unacceptable	Unacceptable-Management Decision Required	Acceptable with Review by Management
Occasional	Unacceptable	Unacceptable-Management Decision Required	Unacceptable-Management Decision Required	Acceptable without Review
Remote	Unacceptable-Management Decision Required	Unacceptable-Management Decision Required	Acceptable with Review by Management	Acceptable without Review
Improbable	Acceptable with Review by Management	Acceptable with Review by Management	Acceptable with Review by Management	Acceptable without Review

Risk is mitigated by decreasing the probability that a given hazard will occur, by reducing the severity of the consequences if a given hazard does occur, or both. Using risk mitigation as a design objective promotes a system development in which safety requirements are integrated at the earliest life-cycle phases. Further risk mitigation is achieved through appropriate operational procedures and assured by properly trained personnel.

However, some residual risk will remain after the best attempts at mitigation through proper design and operational procedures. This residual risk must be judged acceptable for the system to reach the deployment stage. Analysis of deployed systems serving other transportation modes will be required to assess the levels of risk assumed in these existing systems. The identified range of assumed risk can be adopted as an appropriate goal for maglev systems.

3.2.5 System Characterization

Although advanced maglev system prototypes exist, the basic assumption used in this study is that the maglev system is in the concept exploration phase and little is actually known about the system architecture and component design. A few limited assumptions were made as to the characteristics of the maglev system in order to better inform the engineering judgment used to assess the existence of a hazard and its associated probability and severity. The assumptions used are:

1) No specific maglev system design;
2) More than 90% of the guideway is elevated 3m or more above ground;
3) Maximum speed of 134 m/s used in most analyses, with slower speeds around stations;
4) 40-year nominal system life; 300 MPH
5) No specific guideway shape/construction;
6) No specific number of vehicles, length of guideway, number of stations, number of switched sections;
7) Operational procedures are roughly analogous to Transrapid when addressing individual hazards;
8) Standard design practices applied;
9) No specified geographical region;
10) No passenger restraints;
11) Guideway switches encountered at high speed.

As the development cycle proceeds and more is known about the likely system configuration, characteristics, probable route location and lengths, and the number of vehicles, then this preliminary hazard assessment can be extended and refined. Some hazard probability estimates depend directly on these parameters, for example, the switch failure probability is proportional to the number of switches. Hazards that are proportional to these parameters have generally been noted in hazard tables.

3.3 RISK IDENTIFICATION

Risk identification is an ongoing process throughout the maglev system life-cycle. Most, but not all, of the identified risks will be reduced significantly as the maglev system design matures. The risks identified in the current pre-concept definition phase of the maglev system life-cycle will be mitigated using methods which have not yet been established. The MIL-STD-882B methodology calls for the hazard severity to be “a qualitative measure of the worst credible mishap.” Taking a conservative approach, the risks assigned in this study assume that the risk will not be mitigated unless it appears obvious that standard design or construction techniques will be adequate.

Many maglev risks have been assessed as "unacceptable" by this study. This should not cause the misleading impression that maglev will be inferior to existing modes of transportation. The many "unacceptable" risk ratings are primarily due to the fact that the methodology employed classifies the expectation of single death as "unacceptable," and because no special mitigation has been assumed for these hazards at this stage of system development. Thus the expected operational maglev risk will be substantially less than identified here because measures will be incorporated to reduce risks associated with the identified hazards. The primary new risk introduced by maglev is due to its very high speed ground-level operation using a light-weight vehicle.

Existing transportation modes operate with fatalities and have implied risk assignments of "acceptable with management review." U.S. automobile accidents cause 50,000 deaths per year (reference 29). Automobile risks are not an appropriate reference for maglev transportation risks because automobiles are not operated by a sanctioned employee. Further, passengers have some control over the magnitude of automobile risk incurred. The public will accept high automobile risk because of their perception of controlling risk and because of the flexibility and other benefits provided by automobile transportation.

U.S. airlines and railroads (passenger, commuter, and freight) each incur hundreds of deaths each year (reference 29). The scale of operations of these systems is very large. The airline system, for example, delivered over 330 billion passenger revenue miles in 1988 (Ibid.). In spite of these deaths, the systems continue to operate, implying "acceptability" of these risks. If these accidents were due to one or a few distinct hazards, then the risk associated with these hazards might indeed be correctly categorized as "unacceptable" and mitigation measures would be required. But the accident and casualty rates of existing airline and train systems represent the combined accident rates due to many individual hazards. This combined with the very large scale of operations means that these transportation modes must be considered from a risk perspective to be either "acceptable" or "acceptable with review by management." It also means that the benefits received are perceived to outweigh the risks incurred. This maglev study does not address benefits or attempt to compare risks against the benefits received.

System studies conducted during future maglev development life-cycle phases will evaluate the relationships between design options. Allocations between vehicle, guideway, and wayside systems and/or procedural solutions will be made to mitigate risk through reduction of the severity and/or frequency components of each identified hazard. The Technology Assessment (Task 2) activity of this study will analyze specific sensor-based technologies as a means to cost-effectively mitigate the risks that accompany these hazards.

This section describes the individual hazards, by category, from the greatest to the least risk. The hazards within each risk level are presented in order of decreasing severity and, within each severity level, in the order of decreasing frequency. Thus, the highest risk and most severe hazards are at the top of each table.

3.3.1 Obstruction and Fouling Hazards

Hazards identified in this category obstruct and/or foul the maglev system vehicle guideway or operational envelope. Consequences of these hazards may be damage to any portion of the maglev system or degradation of system performance.

The operational envelope is the volume of space directly above the guideway, the width and height of the vehicle, plus specified clearance and safety margins, and extending over the entire length of the guideway. The active portion of the operational envelope, for a given vehicle speed, includes the vehicle and the space immediately ahead in which the vehicle could stop safely.

The vehicle can stop safely, from an operational speed of 134 meters per second without causing disruption to passenger activity. A comfortable deceleration of 0.1g will require more than 8000m to reach a full stop from 134 m/s. This active operational envelope shrinks in length as the vehicle speed diminishes. The acceptable force on passengers in an emergency braking scenario is not yet defined, but would result in a shorter "emergency" operational envelope at a given vehicle speed.

A fouling hazard is characterized here as a hazard which results from some substance or material adhering to the guideway or to the vehicle and causing degraded system performance (e.g.,clearance tolerance violations, clogged sensors). Table 3.3.1-1 lists the identified obstruction and fouling hazards along with the risk, severity, and probability associated with each hazard. A reference to the paragraph describing the hazard is also provided. There are a number of Obstruction and Fouling hazards which could result in death or system loss. It is noted that many of the obstruction and fouling risks are believed to be significantly mitigated through use of an elevated guideway. Reference 5 anticipated that the guideway would be "necessarily" elevated because of the maglev operational speed and the expected service frequency, coupled with the expected lightweight train design. Guideway design can also significantly impact the obstruction and fouling hazard probability. For example, guideway designs with large open areas down the center will provide reduced surface area suitable for resting objects.

Obstruction and fouling hazards are organized into four groups: Large or Heavy Object (3.3.1.1); Humans (3.3.1.2); Small or Light Objects (3.3.1.3); and Weather (3.3.1.4). These groupings facilitate a description of general characteristics for each group. Each hazard identified in Table 3.3.1-1 is described individually within the groups below.

3.3.1.1 Large or Heavy Objects

Large objects are defined here to be greater than 7 kg. This figure is arbitrary, but is the weight of a large bird which might alight on an elevated guideway. It is not expected that the lightest objects of this group would result in substantial damage to a properly designed maglev vehicle. However, for this study, large objects hit by the maglev vehicle at top speed (134 m/s) are assumed to be catastrophic to the train (and to the obstructing humans or animals) unless satisfactory mitigation methods are developed.

The hazards in this group are all classified as "catastrophic" with respect to severity because of the high speeds involved and the expected light-weight train design. Reference 5 commented that "light weight vehicles of the present design [circa 1986] are particularly susceptible to collision damage". The FRA reported that conventional railroads experienced 32 accidents during 1989 due to objects on or fouling the tracks (reference 6) This accident rate (on a per km basis) cannot be directly transferred to maglev because most of the guideway will be elevated. It is reasonable to expect that during the life of a maglev system, at least 10 large objects will be encountered, which is why these hazards have been classified as probable. The exception is for heavy objects thrown onto the guideway by vandals; we expect that this will happen several times per year or more (unless appropriate mitigation measures are applied). Accordingly this hazard will occur "frequently."

Table 3.3.1-1 Obstruction and Fouling Hazards

Hazard	Risk	Severity	Probab.	Paragraph
Large or heavy objects thrown from above guideway	Unacceptable	Catastrophic	Frequent	3.3.1.1
Trespassers	Unacceptable	Catastrophic	Frequent	3.3.1.2
Impinging cars and trucks	Unacceptable	Catastrophic	Probable	3.3.1.1
Large animals on guideway	Unacceptable	Catastrophic	Probable	3.3.1.1
Rockfalls, debris, limbs on guideway	Unacceptable	Catastrophic	Probable	3.3.1.3
Fouling by vehicle on adjacent track or guideway	Unacceptable	Catastrophic	Probable	3.3.1.1
Maintenance personnel on guideway	Unacceptable	Catastrophic	Probable	3.3.1.2
Suicides	Unacceptable	Catastrophic	Probable	3.3.1.2
Train at unknown or wrong location	Unacceptable	Catastrophic	Probable	3.3.1.1
Other vehicles intentionally on guideway	Unacceptable	Catastrophic	Probable	3.3.1.1
Objects hung above guideway	Unacceptable	Critical	Frequent	3.3.1.3
Train component falls on guideway	Unacceptable	Critical	Probable	3.3.1.1
Snow, Ice, standing water	Unacceptable	Critical	Probable	3.3.1.4
Extreme hail,rain, and lightning	Unacceptable	Critical	Probable	3.3.1.4
Dirt and mud	Unacceptable	Critical	Probable	3.3.1.4
Projectiles	Unacceptable	Marginal	Occasional	3.3.1.3
Small rocks, bottles, tools etc.on guideway	Acc. w/rev.	Negligible	Frequent	3.3.1.3
Small animals on guideway	Acc. w/rev.	Negligible	Frequent	3.3.1.3
Magnetic materials	Acc. w/rev.	Negligible	Frequent	3.3.1.3
High winds, tornadoes, microbursts	Acc. w/rev.	Negligible	Frequent	3.3.1.4

An elevated guideway will substantially decrease the chance of encountering a large object. Reference 7 observed: "the design of the system must include the prevention of heavy objects impinging on the right-of-way and causing massive damage to the track system or vehicles...."

A number of the hazards identified below result from coincident, or shared, right-of-ways. These include impinging cars and trucks, objects thrown from above the guideway, fouling by adjacent vehicles, train components dropped from dual-use guideway/railway, etc. Battelle (reference 8) is currently under contract to the Volpe National Transportation Systems Center (VNTSC) to perform a study of shared right-of-way hazards that will provide additional insight into these particular hazards. An assessment of the safe distance required between the operational envelopes of adjacent or intersecting transportation modes will be derived as part of the Battelle work.

Impinging Cars and Trucks

Cars and trucks may impinge on the guideway from shared parallel or crossing right-of-ways, where the other right-of-way is a highway. Reference 7 noted the possibility of "unusual" car or truck accidents. This hazard is more probable when the highway has an elevation equal to or greater than the elevation of the guideway.

Large Animals on Guideway

This hazard includes animals of 7 kg and larger, the largest probably being the size of cows. The larger animals would only be expected on near-grade level portions of the guideway. This hazard would be increased in rural and suburban areas containing a large population of large animals such as deer, moose, and farm animals. The probability of striking larger animals can be mitigated through use of elevated guideway, fencing around unelevated portions, and object-detection systems.

Large or Heavy Objects Thrown from above Guideway

Bridges and buildings with accessible points located above the guideway elevation allow heavy objects to be thrown onto the guideway, in front of, or at, the maglev vehicle. Maximum object weight may be on the order of 75 kg which is approximately the weight that two men can comfortably lift.

Another hazard related to bridges over the guideway or to adjacent elevated streets and highways is the potential for vehicles to crash off the bridge onto the guideway, or for objects to bounce from a vehicle onto a guideway. The significance of these hazard sources, (and what distinguishes them from other heavy objects on the guideway or impinging vehicles) is that very heavy objects could end up on the guideway at an unexpected location.

The probability of this hazard increases with population near to the guideway and with the number of right-of-way overpasses and adjacencies. At the same time, these built up areas are less likely to permit maximum speed vehicle operation, thus decreasing impact velocity and severity, and increasing the time available to detect the hazard.

Fouling by Vehicle on Adjacent Track or Guideway

If mixed mode operations are to be employed, the operational envelope of the maglev vehicle could be fouled by oversize objects carried by freight vehicles on an adjacent track or guideway. Fouling would occur on shared right-of-ways, and be caused by misloaded cargo, oversized cargo, an accident, or cargo which has been misrouted. Mitigation methods for this hazard would include use of standards, establishing suitable minimum separation distances for shared right of ways, fencing or barriers, and object detection.

The FRA reported (reference 6) that there were 13 accidents in 1989 due to equipment on or fouling the track. During the same year, there were 10 accidents due to oversized and misrouted loads. On a per pathway mile basis we would expect that this hazard would be less probable for maglev since careful attention will be paid to this problem during design. Mitigating techniques that are likely to be applied include careful selection of spacing and barriers between the shared right-of-ways and the use of elevated guideway. However at this phase, it is reasonable to expect that such a hazard might occur 10 times in the 40-year life of a maglev system. Thus the hazard frequency is estimated to be probable.

Other Vehicle Intentionally on Guideway

A few incidents of other vehicles placed intentionally on the guideway are expected on elevated guideway sections. These include thrill seekers on motorcycles, skateboards, and bicycles. On grade-level guideway, all vehicle types may be present. Sources at grade-level include accidents from shared right-of-ways, thrill seekers, and drunk drivers. Some guideway shapes may discourage this problem. For example, a guideway which is "U" shaped and does not have a continuous bottom piece may be difficult, or unpleasant for thrill seekers to negotiate.

Train Component Falls on Guideway

Maglev train components may fall from the vehicles onto the guideway and be hit by a following train. Actual components, and their characteristics, for which this is a possibility can be identified once a train design is selected. Sources of this problem would be improper maintenance, infrequent inspections, excessive vibration, and poor vehicle design. On any line segments which have dual-use railway and guideway overlaying one another, there will be an additional hazard from possible component and cargo droppings from conventional rail trains.

Train at Unknown or Wrong Location

This hazard may be broken into related subhazards. 1) A train may be moving at a wrong location: i.e., it is not where it was scheduled to be, and that is not known; 2) it may be "dead" at an unknown and unreported location; or 3) it may misreport position and be either moving as commanded and scheduled, or stopped. These problems may be caused by subsystem malfunction due to failure, design defect, or vandalism. This hazard would be exacerbated if dual-use railway/guideway or similar combined configurations are used.

Some system designs may inherently prevent train movement if position is not reported correctly, e.g., fixed stator systems. Reference 7 commented, "The capability for rapid braking and positive control of vehicle spacing inherent in the Linear Synchronous Motor system of propulsion is very important to safety...."

3.3.1.2 Human Obstructions

The risk is to the individuals and to the vehicle. Kinetic energy is proportional to the square of the velocity. Thus, a maglev vehicle could potentially receive 9 times the energy from striking a person as a conventional train going one-third the speed of the maglev vehicle. This coupled with the expected lightweight train design means that there is substantial risk to the vehicle at high speeds, as well as certain risk to the individual.

The hazard frequency will be increased near larger cities but the severity may be reduced because the maglev vehicle is more likely to operate at slower speeds. However, the hazard can occur at top speed and the severity of the hazards in this section is "catastrophic" because any person being hit will probably be killed. The probability of striking a trespasser is judged "frequent" because of the relatively high rate experienced by conventional rail. Suicides and maintenance personnel on the guideway hazards have been judged "probable" because it is expected that these hazards have the potential for occurring at least 10 times during the life of a maglev system. It is likely that some trespassers killed by conventional rail are really suicides. With this in mind, the frequency of suicides to be expected in a maglev system could be much greater than 10 during the system lifetime.

Maintenance Personnel on Guideway

Reference 9 reports that, between 1966 and 1974, 26.7% of the 1,417 U.S. railroad employees killed in railroad accidents were "struck or run over at places other than public rail-highway crossing". If the guideway is elevated, or if it requires less maintenance work per mile, per year, than conventional rail, then fewer employees would be exposed to the risk of being hit by a maglev vehicle. At the same time, if egress from the guideway is difficult, then a worker who is caught off-guard may be at very high risk on an elevated guideway.

Trespassers

Reference 9 reported that during the 1966-1974 period 5,403 trespassers were killed on U.S. rail right-of-ways. (This figure does not include employees or those killed in grade crossing accidents.) Reference 6 reported 641 trespassers killed in 1989, which is slightly higher than average for the earlier period.

Elevated sections will discourage trespassers from attaining the guideway. Unfortunately, for those that do reach the guideway, exiting promptly may be difficult. Trespassers may climb or walk onto elevated sections and then be afraid to jump out of the way of the train (if, indeed, the train is noticed in time).

European railroads have less of a problem with trespassers than the U.S., perhaps because there are more frequent trains and they are relatively quiet. Thus walking on the tracks is perceived as unacceptably dangerous. This is in contrast to the U.S. where the trains on many lines are infrequent and noisy.

Maglev service is expected to be quiet and frequent, and most of the guideway will be elevated. Therefore, it would be reasonable to expect that the number of trespasser deaths per mile of right-of-way will be substantially reduced from current values experienced in the U.S. rail system.

Suicides

Reference 10 reports that the effect of suicides on a train system is often much greater than planners realize. In some cities, up to half of the suicides occur in rapid transit systems. Washington, D.C. MetroRail officials reported an average of 8 suicide attempts per year in the D.C. system, of which half resulted in death. (personal communication). System planners often ignore the problem on the basis that it is outside their area of control and responsibility. There are real economic benefits to the mitigation of suicides, in addition to the obvious humanitarian benefits. Suicides can shut down transportation systems for hours during peak travel periods. Suicides, and other system-related deaths, can result in harmful mental health effect on operators and maintenance personnel. Affected personnel can take months to fully recover (reference 10).

3.3.1.3 Small or Light Objects

The hazards "small rocks, bottles, tools etc. on the guideway", "small animals on guideway", and "magnetic materials stuck to guideway", were all judged to be of "negligible" severity because of their small size, and because these hazards will occur frequently the basic system design must tolerate these hazards with no degradation.

Rockfalls, Debris, and Limbs on Guideway

Rockfalls would be expected primarily on unelevated guideway sections. Limbs would appear in areas with more trees and are more likely on guideway sections with lesser elevation. Debris would include vegetative matter and material from decayed or damaged structures. Falling leaves may result in slippery surfaces which could cause personnel slips and falls, and reduced emergency braking effectiveness. Wet elm leaves, for example, are particularly slippery. Contributing factors would be areas of elevated terrain, steep slopes, or cliffs near the guideway; presence of older forests or dying large plants; presence of geological features conducive to rock slides; presence of old, damaged, or low quality structures. The incidents of this hazard will be increased during and following violent storms.

This hazard has been judged potentially "catastrophic" because fatal accidents or accidents which cause system loss are believed possible with sufficient quantity of debris on, or fouling the guideway. The probability is judged only "probable" because, while rockfalls, debris, and limbs are common in the environment, most of the guideway will be elevated, making it difficult for these objects to reach the guideway.

Objects Hung above the Guideway

Hazards here could include downed power and communications wires and cables, sagging or broken elevated pipelines, and fallen limbs blown in the vicinity of guideway. Also included are objects hung from bridges and elevated pipelines over the guideway.

Physical strength of lines and electrical current are the main hazards. Small lines may simply be snapped by the maglev vehicle. Largest lines, for example, cross-country high tension lines, could physically damage the maglev vehicle. In addition, the electrical current could pose an electrical hazard.

Reference 11 describes this problem for catenaries used with commuter and Amtrak trains. There have been a number of accidents (18 during a three year period) involving those trains, and their pantographs and catenaries. While maglev itself is not expected to use catenaries, there is a risk on shared right-of-ways where the sharing system uses catenaries. Further, electrical power transmission lines must be considered as a risk.

This hazard was judged to be of "critical" severity. It is thought that the objects which would be hung above the guideway would be small, and the primary danger was potentially severe injury to the vehicle operator. Also, it is possible that at the locations most frequently subject to this hazard, high population areas, the vehicle is less likely to be at full speed. The probability was judged "frequent" or likely to occur ten times a year or more. Note that mitigation of this hazard by screening or fencing at all susceptible locations would substantially reduce this probability.

Small Rocks, Bottles, or Tools on Guideway

Small objects may cause minor damage to the vehicle, but it is presumed that vehicle design will prevent more than minor vehicle damage. Since objects of this size may be hit regularly at the highest speeds, it would be appropriate to require that the vehicle design withstand objects of this weight and less with no damage when travelling at top speed.

Glass objects will result in glass shards on the guideway. This in turn could clog switching mechanisms or guideway expansion joints. Maintenance personnel's tools and components forgotten on the guideway may be a significant source of unwanted objects.

Small Animals on Guideway

This category includes animals weighing less than 7 kg. On elevated portions of the guideway, animals would be limited to flying, and some climbing, species. Since this is a frequent hazard, the vehicle must be designed to tolerate the impact of these small animals. It may be possible to mitigate this hazard in high animal population areas through use of fences, elevated guideway, warning noises or predator images.

Magnetic Materials

Residual magnetism in guideway components could allow some materials to stick to the guideway. Further, metallic objects on or near the guideway could be drawn to the train magnets. Reference 5 noted: "Any ferromagnetic debris on the guideway beam running surface would be attracted toward the vehicle superconducting levitation magnets. The intense magnetic field of the on-board magnets could result in an appreciable impact of such debris on the body shell ....inspection ...would prevent any ferromagnetic debris induced physical damage to the magnet cryrostat."

Projectiles

This category is distinct from the other small object hazards because it affects the side of the train in addition to the front. Vandals throwing rocks have the potential for damaging train windows or other train components, and could injure passengers if rock or damage fragments enter passenger or crew compartments. The source is vandals as well as objects accidentally thrown into the operational envelope by vehicles on shared right-of-ways.

Further, objects hit by the train will sometimes be ejected from the guideway at high speeds, and thereby present a hazard to nearby vehicles (shared or co-incident right-of-ways), persons and property. Glass objects, for example, may shatter when hit and send glass shards away at high speed. The hazard probability increases in areas where the highest numbers of objects on the guideway are expected and where increased numbers of persons or valuable property are expected near the system right-of-way.

3.3.1.4 Weather

Snow and ice can be expected to accumulate on the guideway of maglev systems built in high snow areas. Reference 6 noted that in 1989 there were six conventional railroad accidents attributed to "snow, ice or mud on track". The system design for these geographical areas must consider the effect of these hazards in the guideway and vehicle design, in order to prevent derailments, reduction in emergency stopping capability, and object hazards from loosened ice sheets.

The hazards "snow, ice, and standing water" and "extreme hail, rain" were judged to be of severity "critical" because of the potential for severe injury. It is expected that good design practices will prevent derailments, but not necessarily injuries, due to snow or standing water. Likewise, good design practices should prevent hail from breaking the wind screens and causing fatalities, but injuries may still occur. These hazards could be expected to cause incidents at least ten times during the life of a system, therefore they have been classified as "probable".

Snow, Ice, and Standing Water

Hazards associated with winter storms include ice sheet and heavy snow buildup on guidance rails and the guideway. The frequency and extent of the hazard will vary with geographical region.

Reference 12 reported that the Canadians were considering a system with a large magnetic gap that would, among other things, "reduce the effect of snow and ice build-up on the guideway."

Reference 5 reported that:

> "Ice accumulation on the guideway from freezing rain could significantly reduce the emergency braking deceleration when sliding the vehicle on skids.... The exterior bottom panel of the vehicle body shell may have to be reinforced to absorb the impact of ice sheets which could be stripped off of the guideway by the sliding skids. Such local body shell reinforcement would also provide protection against ice which might be loosened from the guideway by the aerodynamic action of traversing vehicles, particularly in warming weather conditions after freezing rain with induced current heating of the guideway levitation sheets by trainsets which have previously passed."

Reference 12 suggested the use of snow blowers for snow removal, and claimed that for the Canadian EDS and for Transrapid, winds greater than 5 mph would sweep the guideway clear. It was expected that drifting would occur in winds of 3-5 mph. The same reference expected "excess accumulation" twice per winter on a route between Quebec and Toronto.

Snow and ice removal requirements vary with the guideway shape. Reference 12 claimed that the Japanese EDS and mixed-Mu permeability maglevs, which use 'U'-shaped guideways "will require prompt snow removal service to avoid compaction of snow trapped in corners."

Standing water would only be expected to occur on grade-level guideway sections. Flooding would increase the likelihood of this hazard.

Extreme Hail, Rain and Lightning

The U.S. experiences weather much more severe than is normally found in Germany or Japan. Either the vehicle design must withstand harsh weather events such as extreme hail, rain, under the worst circumstances, i.e. full speed, or high speed/curve operation, or these hazards must be detected and operational procedures applied to mitigate the effect of the encounter, or the risk must be accepted. These hazards are associated with thunderstorms. Hazard probability is proportional to thunderstorm frequency and intensity.

Lightning striking the vehicle or guideway could damage either. Power circuits, communications, and control systems could be disrupted temporarily or permanently. Lightning is caused by thunderstorms. The frequency of thunderstorms may be estimated from historical data available from the National Climatic Center, Asheville, North Carolina.

Dirt and Mud

Accumulated dirt and mud have potential for clogging the guideway and guideway sensors. Guideway sensors are of most concern, though in most designs, of course, the sensors will be protected. If optical position sensing were used this would, perhaps, be more significant than if other position sensing methods were used. Primary sources are wet regions, dirty trains, the blowing of dirt or dust onto wet guideway, and perhaps, animals.

The "dirt and mud" hazard was rated "critical" because of its potential to cause injury through disrupting control system sensors. It is expected that catastrophic accidents will be avoided by use of good design practice which expects occasional disruption of sensor information. Because of the expected use of elevated guideway, this hazard has been classified "occasional" meaning that it may occur at least once during a maglev system lifetime.

High Winds, Tornadoes, and Microbursts

Very high winds, particularly on curves, could present challenges. The Japanese Shinkansen control center has warning lights for high winds; warning levels are set at 20, 25, and 30 m/sec. (reference 11). A brief analysis appears in reference 5. System designs must be reviewed for ability to operate under maximum U.S. sustained and gust wind conditions. The source of this hazard is local winds and they are a function of weather systems and thunderstorms. Note that local winds may be intensified by local geographical features.

Tornadoes and microbursts are more common in the U.S. than elsewhere. These hazards are characterized by extremely high wind velocities and flying debris. Microbursts are small scale (1/2 to 2 km diameter) outflows of air which may produce surface winds of 75 knots or more.

The National Climatic Center, Asheville, North Carolina, maintains historical records which can be used to estimate peak winds at a particular location. Reference 13 in turn references two reports which may be used to assess tornado and hurricane winds and their expected frequency. The first is a National Oceanic and Atmospheric Administration (NOAA) report entitled, "Tornado Safety" which was done as part of an evaluation of hazards to nuclear plants. The second is a NOAA report entitled "Tropical Cyclones of the North Atlantic."

These hazards can occur frequently. They have been judged to have severity "negligible", but the severity could be much higher depending on the specific maglev design selected and the actual magnitude of the hazard encountered.

3.3.2 Guideway Integrity Hazards

Loss of guideway integrity is characterized as a condition which is present when a guideway parameter exceeds a design tolerance value and causes the guideway to fail to provide a system function within the specified range identified by requirements.

The guideway performs or supports critical generalized system functions of:

1) Physical support,
2) Monitoring and control,
3) Power transmission, levitation, propulsion, braking, and guidance.

Guideway structural components are responsible for physical support. Structural components of elevated guideway consist of the subterranean footing, columns or pillars, and girders. At-grade guideway often consists of footings or a foundation and the girder. The girder itself must remain capable of bearing load under the static and dynamic forces of a fully loaded vehicle from zero to full rated speed. The girder must remain stationary in vertical and horizontal planes (minor exceptions associated with turnouts). The girder must remain in position under static and dynamic loads. Columns, or footings in the case of at-grade guideway, support the girder. Failure of the girder to maintain physical support is often most easily detectable at the column or footing-to-girder interface because this is where misalignment deflection is greatest and/or occurs first.

Resonance and damping of the girder is tuned to the vehicle for static levitation (some maglev system designs do not support static levitation) and movement over the guideway at a range of velocities. Maintenance of the intended dynamic characteristics of the girder is critical because excessive deflection or resonance can trigger loss or indicate impending loss of physical support. Failure to maintain dynamic parameters within specified tolerances is usually most detectable at mid-span due to increased deflection at this location.

Monitoring and control is critical to the safe movement of a vehicle along the guideway. Many monitoring and control components are associated with switches to detect and control switch position. A safe maglev network would contain switches with position indicators and actuators, lock indicators and actuators, and vehicle movement interlocks. Failure of switch monitoring and control may result in two vehicles colliding.

Convention establishes monitoring and control of vehicles into blocks. The blocks may be of fixed or varying length. The synchronous excitation nature of long stator propulsion precludes healthy vehicles from moving at different velocities within a power and control block. Vehicles may not remain healthy (e.g. capable of maintaining individual vehicle levitation, guidance, power transfer, communications, control, etc.) however, and therefore could close upon one another at great differential velocities.

Detection of guideway physical integrity may also depend upon monitoring and control functions and components. Breakwires, seismic detectors, communications lines, etc. are possible components of the monitoring and control subsystem for guideway integrity.

Finally, guideway integrity may depend upon continuity of power transmission, levitation, propulsion, braking, and guidance functions. These functions are generally associated with keeping network vehicles moving, corruption of which, may not merely shut down vehicle movement but may also lead to threatening circumstances. Without power, a gliding vehicle could impact a stationary vehicle.

Stationary components that may contribute to these functions include:

1) Stator windings,
2) Supply cables,
3) Controllers,
4) Disconnectors,
5) Braking contactors and choppers,
6) Braking resistors,
7) Circuit breakers,
8) Output transformers,
9) Inverters,
10) Rectifiers,
11) Commercial grid service,
12) Uninterruptible power supplies, etc.

Table 3.3.2-1 lists guideway integrity hazards and their estimated probability, severity, and risk. Paragraph references in the table are to the paragraph of this section describing the hazard.

Guideway integrity hazards are organized into four groups: Gradual Guideway Alignment Degradation and Distortion (3.3.2.1), Switch Problems (3.3.2.2), Missing and Severely Misaligned Guideway Sections (3.3.2.3), and Guideway Component Failure or Separation (3.3.2.4). These groupings facilitate a description of general characteristics for each group. Each hazard identified in Table 3.3.2-1 is described individually within the groups below.

Table 3.3.2-1 Guideway Integrity Hazard

Hazard	Risk	Severity	Probab.	Paragraph
Mis-aligned joints	Unacceptable	Catastrophic	Frequent	3.3.2.1
Series of Mis-aligned joints	Unacceptable	Catastrophic	Frequent	3.3.2.1
Guideway switch failure	Unacceptable	Catastrophic	Probable	3.3.2.2
Switch indication failure	Unacceptable	Catastrophic	Probable	3.3.2.2
Earthquake	Unacceptable	Catastrophic	Probable	3.3.2.3
Washout	Unacceptable	Catastrophic	Probable	3.3.2.3
Missing or severely mis-aligned guideway section	Unacceptable	Catastrophic	Occasional	3.3.2.3
Distortion of Guideway	Unacceptable	Critical	Frequent	3.3.2.1
Separation of rails from guideway structure	Unacceptable	Critical	Probable	3.3.2.4
Guideway components mis-installed or vibrate out of place	Unacceptable	Critical	Probable	3.3.2.4
Aging of Components	Unacceptable	Critical	Probable	3.3.2.4
Effect of emergency landing skid use on guideway	Un./dec. req.	Marginal	Probable	3.3.2.4

3.3.2.1 Gradual Guideway Alignment Degradation and Distortion

Guideway alignment and guideway distortion are related. Factors leading to alignment degradation may result in distortion. Alignment refers to the smoothness of transition between interfacing adjacent sections of guideway. Guideway distortion refers to the deviations (in the field) from the guideway shape nominally required and specified on drawings.

Guideway mis-alignment and distortion may result in high force interactions between the vehicle and the guideway during normal operation, including landing, and especially during use of the emergency skids. In this context, reference 12 reported the following. "Live load impact is generated by inaccuracies of the guideway, as well as by its deflection....large impact loads may be generated during touch-down of a dynamic maglev vehicle and its running over joints and irregularities of the surface."

Guideway tolerances are generally small compared to other civil structures of similar scope. Maglev system designs, such as Transrapid, which use very small clearance distances place severe constraints on guideway alignment and distortion. Reference 7 noted that "the combination of small clearance and high speed poses severe constraints on the track. It must be laid out very accurately, with only small deviations (millimeters) from a perfect plane..."

Therefore, existing methods of construction analysis and actual construction may be severely stressed. Reference 12 noted that "the relatively lightweight characteristics of maglev and the large horizontal loadings at high speed lead to the unusual action of piers and footing due to high overturning moments.... Tolerances of superstructure geometry should be considered during geotechnical investigation. The differential settlement criteria and demands for stability of foundation strata may be substantially more strict than the ones valid for conventional modes, including at-grade level alternatives. Tectonic conditions, seismic data and zones of local geologic instabilities should be well defined."

Gradual Guideway Alignment Degradation - Mis-Aligned Joint

Gradual guideway alignment degradation may be due to differential guideway settlement, seasonal foundation movement due to frost heave, ground water variations, or structural creep. Gradual alignment degradations are characterized by a slow change of the designed or installed guideway alignment. The most rapid of these alignment changes might be due to frost heave and ground water variations, causing significant alignment changes over several days. Causes for the gradual decay of the guideway alignment include inadequate foundation preparation, poor geotechnical routing/surveys, poor system design (required tolerance for guideway alignments too stringent for the available construction methods or local geotechnical features), construction materials below specified quality, or weak quality controls.

Locations which have high expected geotechnical variations may preclude selection of maglev systems with small magnetic levitation gaps. For example, reference 12 reported "a...large gap (6 inches) is dictated by the geological conditions and ground upheaval due to heavy frost in the Toronto-Montreal corridor." The same reference mentions a study performed by the Canadian Institute of Guided Transportation at Queens University which, in a electrodynamic guideway design, used a large gap which could tolerate variations of ± 9/16-inch per 82 foot guideway span.

This hazard could cause death or loss of the system if these alignment shifts are not carefully monitored or otherwise mitigated. Since small alignment shifts will occur continuously, this hazard is potentially "frequent".

Sequence of Mis-Aligned or Distorted Guideway Deviations

The spatial relation of guideway deviations along the length of the guideway may be as important as the magnitude, for small magnitude deviations. The spatial relation between along-path errors, and their magnitudes, impacts the design of the levitation control system and its requirement to perform within specification. If the spatial frequencies of the errors are very high, then the errors may be "averaged" out by the control system or the mass of the components. If the error spatial frequency is low, then the control system may be required to compensate for misalignment. There will be a band of frequencies which will stress the control system and its design. In addition to the impact to the control system, the expected spatial frequency of errors can impact the choice of magnet placement on the maglev vehicle and also passenger comfort. Reference 14 noted that "Short-wave position displacements of the rails at greater amplitudes make high dynamic demands on the layout of the magnets ... Long-wave position displacements of the guideway of excessive amplitudes can no longer be prevented from reaching the passenger compartment ... they result in an adverse effect on ride comfort."

Distortion of Guideway

The guideway can distort due to alignment degradation, structural creep, earthquake, temperature variation, or geotechnical factors. For example, the guideway design or operating tolerances must accommodate solar induced heat distortion.

For a prestressed concrete guideway, long-term deflection will depend not only on creep of concrete but also on loss of prestress in the prestressing strands. The loss of strand prestress will, in turn, result primarily from elastic shortening and bending of concrete, creep of concrete, shrinkage of concrete, and steel relaxation.

Reference 14 mentions "other deviations of the rail surface from the alignment line must be considered in addition to the deflection of the girder, such as deformations caused by temperature differences in the girder owing to weather conditions, and the mounting tolerances of the rail surface referred to the guideway girder."

This hazard could cause severe injury, and has been rated "critical". Distortions due to solar heating, for example, can occur frequently.

3.3.2.2 Switch Problems

FRA statistics report that 74 conventional railroad accidents were due to "switch improperly lined" in 1989 (reference 6). Twenty-one of the "switch improperly lined" hazards resulted in collisions, and 35 in derailments. The same year 82 derailments were attributed to "switch damaged/out of adjustment". These statistics do not directly transfer to maglev, but they do highlight the importance of switches.

The guideway switch must line up two guideway sections within specified tolerances. See Paragraph 3.3.2.1 for the importance of alignment tolerance. The switch should move to a commanded position, and must correctly report whether it is at the commanded position and within alignment specifications. Further, the switch must reliably report position and status information. Possible sources of switch failures are damaged switch components, faulty sensors or switch monitoring, control or communications systems, fouling of the switch components, and vandalism. Environmental contamination, such as ice or snow build-up, could also result in switch failure.

In the event of an unannounced switch or switch position sense failure, the train could go down the wrong guideway and hit another vehicle, object, reach the guideway end, launch from an open ended switch, or enter a construction or maintenance area. Maglev system architectures using linear synchronous motors, and selected block control, may mitigate the risk of these hazards.

Guideway Switch Failure

Switch failure can usually be traced to electrical, mechanical, or sensor failure. Switch position mis-alignment can be due to damaged switch components, wear, faulty sensors or switch monitoring and control systems, or vandalism. Destruction of a maglev vehicle could result from an unlocked or improperly positioned switch. A less severely mis-aligned switch could result in passenger discomfort or injury. A switch set to the wrong position would send the vehicle on a wrong section of guideway and could result in collision, derailment on sections being maintained or under construction, or over-running the end of the guideway.

Reference 12 noted that "maintenance practices should ensure that bearings are functioning properly, expansion joints are not filled with debris, and moving contact plates are clean and well maintained. These aspects of maintenance are seldom given top priority on highway and many railway structures. Resulting distortions would not be tolerable on maglev lines"

The "guideway switch failure" hazard is rated potentially "catastrophic". The probability of this hazard is "probable" because it is expected that there will be many switches, thus increasing the potential for failure.

Switch Indication Failure

Switch status indication equipment is an example of a control system component embedded in the guideway. Failure of switch status indication is distinct from failure of the switch itself; switch failure will be mitigated if the status (failed) is reported correctly. Conversely, if the switch is operating correctly but a wrong position indication is supplied, then disaster may result.

The hazard "switch indication failure" is rated as potentially "catastrophic". The probability of a failure is proportional to the number of switches in the system.

3.3.2.3 Missing and Severely Mis-aligned Guideway Sections

Missing and severely mis-aligned guideway segments can result in derailments or other catastrophe. Maglev system design should be highly resistant to derailment under expected operating conditions. The use of a wrap-around vehicle makes derailment difficult under nominal conditions. A maglev vehicle design considered by Canada was considered "as having negligible chance of derailment because of "1.5 meter downward extending length of the vehicle sidepods which straddle the guideway." (reference 5).

The consequences of derailment occurrences are severe, but thorough and extensive efforts should be applied during the system development phase which would substantially mitigate the risk.

Reference 7 stated: "System must be essentially fail-safe. The Japanese National Railway (JNR) experience is very encouraging in this regard. They have operated test vehicles for years. Deliberately introduced large track misalignments have been studied. These simulate earth movements due to track settling, earthquakes, etc. Track integrity must be maintained. The large track-vehicle clearance allows relatively large tolerance errors in track position to be accommodated by the inherently stable magnetic [repulsive] suspension. This makes the system highly tolerant to earthquakes and other sources of track movement..."

Missing or Severely Mis-Aligned Guideway

Guideway sections could be missing or severely out-of-alignment due to broken columns or downed beams caused by a train derailment, adjacent track accident, impinging vehicle, aircraft accident, construction, washout, earthquake or other event.

Washout

A washout could result in weakened, unsupported or missing section of guideway. Washout locations will depend on geo-technical and hydro-geographic conditions, routing, and the guideway foundation design and preparation. Reference 11 reported two serious passenger train accidents due to washouts.

The probability of a washout may be estimated from examination of geographical and geotechnical features in the local area, along with examination of local and regional rainfall data.

Earthquake

The Japanese Shinkansen control center has warning lights for earthquake detection, both coastal and at substations along the line. Thresholds are set at 40 gals [cm/sec/sec] for the coastal sensors and 80 gals for the substation sensor. (reference 11).

A principal hazard is a loss or mis-alignment of guideway section. Hazard to vehicle due to lateral accelerations during earthquake is an additional consideration. There is a hazard to passengers if there is excessive deceleration of the vehicle due to an earthquake.

The expected earthquake frequency and magnitude can be estimated by geographic region. Reference 13 in turn references a U.S. Geological Survey report which provides data on earthquake frequency, by region, for earthquakes of a specified magnitude and larger. The same reference estimated the probability of destruction of a particular facility in Washington, D.C. as being near zero. The estimated probability of destruction of a similar facility in Los Angeles is 0.00235 over one year.

Large magnetic levitation gaps can help reduce the risks associated with earthquakes, and has probably been an influence on the particular technologies and design gaps chosen by the Japanese. (reference 12).

3.3.2.4 Guideway Component Failure or Separation

Separation of Rails or Stator Packs from Guideway Structure

Metal rails used as landing surfaces, or stator packs that support magnetic levitation, could become loose due to inappropriate design, defective materials, installation defect, temperature cycling, or normal repetitive use. The loose components could then become a hazard, particularly since they may be located in areas which may have small clearances.

Reference 14 notes that "other deviations of the rail surface from the alignment line must be considered in addition to the deflection of the girder, such as deformations caused by temperature differences in the girder owing to weather conditions, and the mounting tolerances of the rail surface referred to the guideway girder."

Aluminum reaction plate caps and metal rails used as landing surfaces, or to support magnetic levitation, could become loose through temperature cycling or normal repetitive use. The loose rails could then become a hazard, particularly since they may be located in areas requiring tight tolerances. The source of these hazards could be design, temperature cycling, normal use, defective materials or installation defects.

Guideway Components Mis-Installed or Vibrate Out of Place

Stator packs or other guideway components could move out of place and obstruct or foul the guideway. Attendant electrical, fire or mechanical hazards may result. Potential sources for this problem include cumbersome installation procedures, unexpected vibrations, quality control.

Effect of Emergency Landing Skid Use on Guideway

Use of the emergency landing skids has the potential for adversely affecting the guideway surface. If usage damages the landing surface, the performance during later use may be affected, including stopping distance, deceleration smoothness, etc. The rate of deceleration is important, particularly because it is assumed that passengers will be unrestrained.

If the landing surface is damaged by use, it could lead to a localized increased rate of weather damage to guideway. The sources of this hazard are design, and use of emergency landing skids, especially at high speed.

Reference 5 emphasized that the surface of the guideway is an important factor in determining the stopping rate and distance under emergency conditions.

Aging of Physical Components

Guideway sensors may degrade with age due to many environmental factors, in addition to general aging. Pejorative environmental factors include long-term exposure to ultraviolet radiation, to heating/freezing cycles, to wind blown grit, to industrial pollutants, to dirt and grease accumulation, and to vibrations.

Metal guideway components may be subject to metal fatigue depending on where they are used in the design. Metal components may also be subject to rust, corrosion, and attack by salt or industrial pollutants.

Gross spalling of a concrete guideway surface may have the potential for degrading guideway performance, both as a source of contaminating material, and as source of roughened guideway surface. Sources of this problem usually are guideway design and concrete quality.

3.3.3 Physical Security Hazards

Table 3.3.3-1 lists physical security hazards along with their estimated probability, severity, and risk. Paragraph references are provided indicating the paragraph of this section which describes the hazard.

Physical security hazards are organized into two groups: Crime (3.3.3.1) and Terrorism (3.3.3.2). These groupings facilitate a description of general characteristics for each group. Each hazard identified in Table 3.3.3-1 is described individually with these groups below.

3.3.3.1 Crime

Eleven years ago, reference 15 noted "Interest has been mounting over the large amount of vandalism that has caused rocks, bullets, and bottles to smash windows and injure railroad employees and passengers riding on trains along major right-of-ways." Reference 13 used Federal Bureau of Investigation's Uniform Crime Reports, and other information, for example, to estimate that the probability of sabotage damage to an airways facility in Cleveland, for example, was 0.0012 in one year. The Uniform Crime Reports shed light on the probability of vandalism and other crime. This series of documents provides crime information by region. FRA statistics report 46 conventional rail accidents due to vandalism during 1989.

Vandalism

Vandalism covers a wide range of potential hazards. Many of these hazards are identified individually as part of this hazard analysis. Examples are objects thrown at the vehicle or onto the guideway. Vandalism would be expected to be increased in areas of high population density.

Table 3.3.3-1 Physical Security Hazards

Hazard	Risk	Severity	Probab.	Paragraph
Vandalism	Unacceptable	Catastrophic	Frequent	3.3.3.1
Terrorism	Un./Dec. Req.	Catastrophic	Remote	3.3.3.2
Bullets	Unacceptable	Critical	Frequent	3.3.3.1
Station crime	Unacceptable	Marginal	Frequent	3.3.3.1
Security of support facilities	Unacceptable	Marginal	Frequent	3.3.3.1
Right-of-way violation by trespassers	Acc. w/rev.	Negligible	Frequent	3.3.3.1

"Un./Dec. Req"=
Unacceptable- management
decision required.

"Acc. w/rev."=
Acceptable with review
by management.

Station Crime

Passengers and maglev employees must be protected from crime in the stations. System facilities must be protected against theft, vandalism and other crime. The risk will be higher for those stations located in high-crime areas.

Maglev stations will be an access point to the guideway for trespassers and others, including thrill seekers and suicide candidates. Most of the guideway will be elevated and difficult to access, therefore the stations may become a prime access spot for unauthorized individuals who wish to reach the guideway.

Security of Support Facilities

System facilities and personnel must be protected against theft, vandalism, and other crime. The risk will be higher in high crime areas and out-of-the-way locations.

Right-of-Way Violation by Trespassers

Right-of-way violation by trespassers can lead to vandalism and trespassers on the guideway. It is expected that most trespassers will do no harm. Separate hazards have been identified for those trespassers engaged in vandalism, or who trespass the guideway. The probability of trespassers will be higher in easily accessible areas.

Bullets

Bullets and shotgun pellets can damage trains and guideway and communications, and sensing equipment. Literature search or FRA experience could determine if particular portions of the system or particular portions of the vehicle are more prone to be targets, and therefore deserve more protection. This hazard will be more common in some geographical areas than others.

3.3.3.2 Terrorism

Terrorism

It may be appropriate to review FAA and airlines studies and countermeasures to determine their applicability to maglev. Terrorism would be expected to increase during some time periods. One study done for the FAA (reference 13) estimated the probability of terrorists damaging various FAA facilities. That study estimated the probability of terrorist damage at a site as being 0.00009 over one year.

3.3.4 "Other" Hazards

Table 3.3.4-1 lists guideway integrity hazards and their estimated probability, severity, and risk. Paragraph references are provided indicating the paragraph of this section which describes the hazard.

"Other" hazards are organized into two groups: hazardous materials (3.3.4.1) and operating systems (3.3.4.2). These groupings facilitate a description of general characteristics for each group. Each hazard identified in Table 3.3.4-1 is described individually within the groups below.

3.3.4.1 Hazardous Material, Fires

Hazardous materials released by accidents on adjacent right-of-ways presents a risk to maglev passengers, crews, and the maglev vehicle.

Reference 9 noted that estimates indicate that uninsulated pressure-tank cars result in "approximately 10 percent annually of all damage to railroad property". The FRA reported that in 1989 there were 3 rail accidents involving hazardous materials and "explosion-detonation or fire or violent rupture". (reference 6). The same source noted approximately 200 accidents per year (1984-1989) in which a hazardous material car was damaged or derailed. There were approximately 50 accidents per year where there was a release of hazardous material. Evacuations resulted approximately 25 times per year. To these figures must be added accidents due to trucks and pipelines carrying hazardous materials.

Table 3.3.4-1 "Other" Hazards

Hazard	Risk	Severity	Probab.	Paragraph
Hazardous material leaking from adjacent pipeline or from vehicles on shared right-of-way	Unacceptable	Catastrophic	Probable	3.3.4.1
Vehicle fire	Unacceptable	Catastrophic	Probable	3.3.4.1
Embedded software control error	Unacceptable	Catastrophic	Probable	3.3.4.2
Human factors induced accident	Unacceptable	Catastrophic	Probable	3.3.4.2
Wayside fire	Unacceptable	Catastrophic	Probable	3.3.4.1
Unrestrained passengers	Unacceptable	Catastrophic	Probable	3.3.4.2
Guideway fire	Unacceptable	Catastrophic	Occasional	3.3.4.1
AC power grid failure	Un./Dec. Req.	Marginal	Probable	3.3.4.2
High-speed clamp-on	Un./Dec. Req.	Marginal	Probable	3.3.4.2
Operator-less train	Acc. w/rev.	Negligible	Probable	3.3.4.2

Reference 11 reported that the second most common type of equipment-caused accidents for passenger trains was fire. There were eleven fires in 3 years. Reference 6 reported six electrically caused fires and two oil fires in locomotives during 1989.
These statistics are not directly transferrable to maglev, but they do indicate that caution is necessary.

Hazardous material leaks

A pipeline accident may leak hazardous material (poisonous, flammable, explosive) in the vicinity of guideway. Poorly maintained pipelines or accidental valve openings could also contribute to the release of hazardous material onto the maglev right-of-way. Trucks and conventional trains carrying hazardous materials on adjacent right-of-ways constitute a risk to the maglev system. Reference 8, a Battelle study, examines these shared right-of-way issues.

Vehicle Fire

Fires can be expected to occur within the vehicle; most will be small, but there is potential for death and loss of system. Good design practices, based on existing codes and system experience must be applied to minimize the risk.

Wayside Fire

Wayside fires may be more dangerous than they first appear. For example: A fire adjacent to the guideway damages guideway component(s); in turn a train stops adjacent to the fire, either due to damaged guideway component(s) or due to operator concern about potential for problem due to fire. Then the maglev vehicle is damaged, and cannot move, and passengers have difficulty evacuating due to fire, smoke, panic, and, perhaps, lack of good exit routes. Flammable material near the guideway would contribute to this hazard.

Guideway Fire

Shorts in the stator winding, combined with combustible material in the guideway, or combustible fluids dripped from the vehicles, could result in fire. If, for example, the maglev vehicle contains combustible liquids and they leak from the vehicle and accumulate at, say, a station stop, then there is an increased potential for fire. Contributing sources could be stator shorts, poor original materials selection, accumulated flammable material, and lack of a detection system.

3.3.4.2 Operational Maglev Systems

Operational maglev systems will face additional hazards beyond guideway integrity and obstruction and fouling hazards and the other hazards previously described. Errors in the maglev vehicle design, failures in maglev components and failures or errors in the operating procedures and their implementation can all contribute to accidents.

Embedded Software Control Error

Undetected software errors in the maglev vehicle, or, perhaps in the system control center could cause loss of control of a maglev vehicle.

The worst case embedded software control error could cause the vehicle (or system) to ignore required speed limits or fail to recognize stop commands. The source is a design error coupled with failure to exercise the error during development or testing.

Human Factors-Induced Accident

Humans will be involved in the operation of a maglev system; humans make mistakes; the system design and operational procedures must recognize and expect this in order to minimize the risk.

Operators and system controllers, and maintenance personnel can become bored or forget to follow procedures. Controls can be misplaced or hard to interpret. Maintenance personnel or operators could 'temporarily' remove or modify safeguards or control system equipment. Any of these events could be the first step in an accident chain. Attention to human factors and a solid automated system design will reduce these risks. The source of this hazard is system development without human factors continuously in mind.

Reference 11 noted that operator error caused half of all injuries in passenger trains during one period. "The accidents were due to obvious causes - collisions or excessive speed derailments due to engineers failing to obey signals or instructions, engineer/dispatcher misunderstandings or incorrectly set turnouts." Reference 15 commented, for conventional rail, "a majority of the causes of train derailments and collisions can be attributed to human causative factors." Reference 9 shows that human factors resulted in between 20-30% of all rail accidents between the years 1966 and 1974. Reference 9 also noted that "operating practices, ineffective training, personal problems, or employee apathy" contributed to these problems. These particular causative factors highlight the requirement to inject human factors knowledge into all levels of system design.

It is anticipated that maglev systems will be much more automated than existing rail systems, and therefore should be inherently more immune to some of the conventional rail human factors problems. But maglev will be more complicated than existing rail and there is potential for new types of human errors.

AC Power Grid Failure

Failure of the power grid supplying the maglev system could cause damage to the maglev vehicle and to the passengers and crew. Careful design will mitigate the risk associated with this hazard.

A review of the hazards which may be caused by ac power grid failure may determine that the severity class can be reduced to "negligible." Reference 5 described the automatic emergency braking that would be required in the event of system power failure.

High Speed Clamp-on

High-speed clamp-on applies only to magnetic attractive systems. Vehicle/guideway design and failure modes and effects analysis can mitigate this hazard. Vehicle control design, verified and validated, is a primary method to mitigate this hazard. Failure mode effects and criticality analysis can be used to determine that individual failures will not cause high-speed clamp-on.

Reference 7 commented that to mitigate this hazard "sufficient redundancy must be built in to ensure reliability at all times..... The servo attractive suspension has a stability issue limited to its very small clearance. The servo system must act much more quickly to prevent vehicle track contact than if it had a clearance comparable to that of the superconducting (repulsive) suspensions."

Operator-less Train

When the train is highly automated, it will be possible for the train to proceed without an operator aboard, or with the operator absent from the control compartment. The possible effects of this on safety will need to be examined. Some hazard mitigation techniques will require very fast response times, which will encourage their implementation in a fashion which does not require, the operator to be "in the loop". Furthermore, to allow for the operator's needs, the operator may not be required to be seated at all times. This hazard is a by-product of the use of highly automated systems.

Unrestrained Passengers

A controlled 0.1g stop from 134 m/s requires approximately 8000 meters and presents little risk to passengers. The instantaneous decelerations experienced during emergency braking actions, and emergency skid stops, have potential for causing death or severe injury to unrestrained passengers. Unrestrained passengers are at substantially increased risk during collisions.

Many times during the operation of a maglev system, anticipatory braking will be required to avoid a hazard. It is anticipated that the system will be designed to provide sufficient advanced warning of hazards to allow use of controlled, gentle braking. However, this may not always be possible. During these events, unrestrained passengers are at increased risk compared to restrained passengers. The overall severity of this hazard is "catastrophic." The overall probability is "probable."

Seat belts offer a partial mitigation to this hazard. Others techniques should be considered, including rearward facing seats, air bags, and other cushioning and constraining devices. The ultimate mitigator is never decelerating at rates greater than 0.1g.

APPENDIX A. REFERENCES

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APPENDIX B. DEFINITIONS

Key definitions for words in this report are defined below. Paragraph references are to Reference 1, MIL-STD-882B.

5.1 Hazard - A condition that is prerequisite to a mishap (3.1.1).

5.2 Hazard probability - The aggregate probability of occurrence of the individual hazardous event that create a specific hazard. (3.1.6). The probability categories used in this study are as follows (References 3 and 4):

Frequent - Not unusual, could occur ten times annually;
Probable - Could occur ten times in maglev system lifetime;
Occasional - Expect to occur at least once in maglev system lifetime;
Remote - Unlikely to occur during maglev system lifetime;
Improbable - Event is so unlikely that it is not expected to occur.

5.3 Hazard severity - An assessment of the worst credible mishap that could be caused by a specific hazard. (3.1.7). The severity categories used in this study are as follows (References 3 and 4):

Catastrophic - Death to individual, loss of maglev system;
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.
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.
Negligible - Less than minor injury. Does not impair any critical systems.

5.4 Mishap - An unplanned event or series of events that results in death, injury, occupational illness, or damage to or loss of equipment or property.

5.5 Risk - An expression of the possibility of a mishap in terms of hazard severity and hazard probability. (3.1.11)

5.6 System Loss - System loss is the loss of use of the maglev system or loss of a system route, due to an accident, for 1 or more days. This loss may be due to guideway damage or malfunction, broken and unmovable trains, or other causes.

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