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Maglev Guideway and Route Integrity Requirements

National Maglev Initiative
Washington, D.C. 20590

DOT/FRA/NMI-92/04

April 1992
Final Report

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

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

AREA (APPROXIMATE)

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

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

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

TEMPERATURE (EXACT)

[(x - 32) (5/9)] °F = y°C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

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

AREA (APPROXIMATE)

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

MASS - WEIGHT (APPROXIMATE)

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

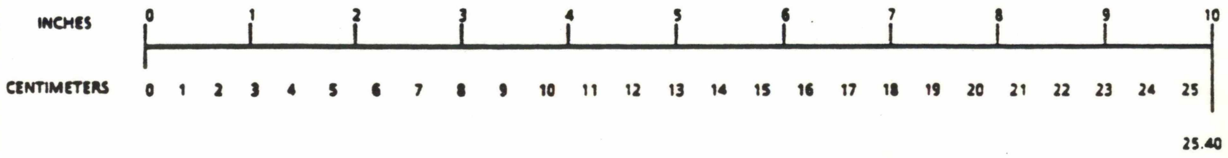
VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

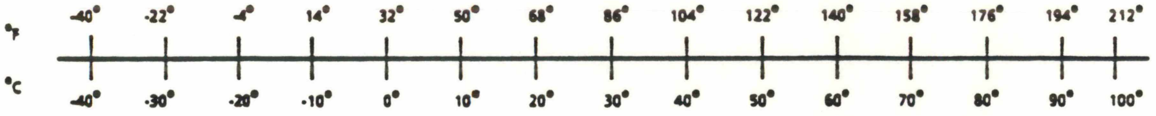
TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH-CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION



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

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16. Abstract

New modes of travel imply new hazards and increased risk from old hazards. Lightweight magnetic levitation (maglev) vehicles, operated at high speed, may be subject to increased collision consequences, compared to conventional rail. This suggests examination of sensor systems and automation.

This final reports summarizes potential safety risks in proposed high-speed maglev transportation systems, examines the prospect for sensor-based mitigation of these risks, and describes a communications architecture to integrate sensor data for control actions. The identified hazards, and their associated risk assessments, are useful for risk mitigation strategy definition and will support analyses during the early phases of system devleopment. The information provided will also support the development of system safety requirements and performance and design specifications. This report is a summary of three interim reports.

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FOREWORD

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

Acknowledgment is gratefully given to the Contracting Officer's Technical Representative, Richard Suever, Army Corps of Engineers, and to the primary reviewers, Candido Damian, Army Corps of Engineers, George Anagnostopoulos, Volpe National Transportation Systems Center, Manuel Galdo, Federal Railroad Administration, and Laurence Blow, Argonne National Laboratory.

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1.0 SUMMARY (ABSTRACT)

Safety is of primary importance in any proposed magnetic levitation (maglev) transportation system. The major emphasis in this task is the safety aspect. Lightweight maglev vehicle design, coupled with high-speed operation, increases the potential severity of accidents and thus demands examination of sensor systems and automated operation. A comfortable 0.1g stop from full speed (134 meters/second) requires over 9 kilometers and 137 seconds. This environment increases the volume of sensor and control data transmitted, reduces reaction time, and calls for more stringent reliability requirements than are necessary for current ground transportation systems.

New modes of travel imply the potential for new hazards or increased risk from old hazards. While potential maglev architectures contain inherently safe features, associated hazards have potentially serious consequences, and therefore require careful investigation. The identified hazards, and their associated risk assessments, are useful for risk mitigation strategy definition, and will support analyses during the early phases of system development. The information provided will also support the development of system safety requirements and the preparation of performance and design specifications.

This report describes potential risks in proposed maglev transportation systems, the prospect for sensor-based mitigation of these risks, and a communications architecture to integrate sensor data for control actions. This report summarizes three interim reports and is provided under Federal Railroad Administration (FRA) contract DTFR53-91-C-00067.[1,2,3]

Risk Identification

The maglev system is in the concept exploration phase and specific system architectures and component designs have not been selected. The approach taken by Martin Marietta to risk identification and assessment is based on a preliminary hazard analysis (PHA), as described by MIL-STD-882B, Systems Safety Program Requirements. The standard provides a comprehensive and practical set of plans and procedures for evaluating and managing system safety. Only those tools and procedures which are needed for a particular system are applied, thus the standard may be used cost effectively on commercial systems.

Forty-eight hazards were identified and divided into four categories:

1) Obstruction and fouling;
2) Guideway integrity;
3) Physical security hazards;
4) Other hazards.

These 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). The definitions selected for severity, probability, and risk are similar to those suggested by the military standard, and are complementary to those used in recent FRA studies.[5]

Hazard probability and severity characterizations assume good standard design practices, without special mitigation techniques. For example, the consist is assumed to withstand impact with lightweight objects, but the guideway is presumed to be fully unshielded, permitting hurled objects to land on the guideway. A few assumptions were made about the characteristics of the maglev system to inform the engineering judgment used to identify hazards and to assess the associated probability of occurrence and severity of consequences. Key assumptions include: 90 per cent or more of the guideway is elevated 3 meters or more above ground; maximum speed is 134 meters per second; the system life is nominally 40 years; operational procedures are roughly analogous to Transrapid; and no particular geographical location is assumed.

Very few of the risks are truly unique to maglev. The primary new risk introduced by maglev is that the combination of high speed (134 m/s) and lightweight construction increases the potential severity of collisions. Of the 48 risks identified, 37 are characterized prior to mitigation as unacceptable and must be mitigated before system deployment. The high number of risks characterized as unacceptable is a result of the conservative methodology (MIL-STD-882B) used which assigns an "unacceptable" risk to any hazard that may result in even a single death over the entire system life. The assumed absence of mitigating system features from this initial analysis also contributed to the number of unacceptable assessments. 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 12 unacceptable risks, such as extreme weather, guideway distortions, and station crime, were judged likely to occur frequently enough that mitigation measures are warranted. The remaining 11 risks, such as small rocks and animals on the guideway, are characterized as requiring judgment by the project management (operators, developers, regulators, and financiers) as to acceptability.

Continued review and substantiation of hazard characterizations will be a part of ongoing safety analyses. Residual risk will remain after the best attempts at mitigation are made through design, passive techniques, sensors, and operational procedures. This residual risk must be judged acceptable for the system to reach the deployment stage.

Sensor Technology Assessment

This report examines sensors for risk mitigation in vehicle-mounted, guideway-mounted, and wayside deployment configurations. Each sensor was assessed for performance in mitigating a hazard, and for technological maturity in that application and deployment configuration. Sensor selection and evaluation included: 13 sensors for obstruction and fouling; 10 sensors for guideway integrity; 7 sensors for physical security and 4 sensors for "other" hazards.

Two promising obstruction sensor technologies include local line sensors and on-vehicle millimeter microwave (MMW) radar. Local very-short-distance (100-meter) guideway section-by-section line sensors would be installed along much of the route. These sensors would employ low-cost narrow infrared, visible light, or MMW transmitters at one end of a section of guideway beam, and a corresponding receiver at the other end of the section of beam to detect obstruction and fouling hazards. Such sensors might not be employed along long straight sections of route where the on-vehicle type of sensor would provide the best performance. Local sensors would be the sole obstruction and fouling sensor for some route geometries.

MMW radar offers value as the last line of defense against obstruction or fouling not otherwise prevented or detected. Vehicle-mounted radar will not detect obstructions or fouling in time to allow a "normal" stopping rate to be used. Hills, valleys, curves, and the normal earth curvature severely limit an on-vehicle, look-ahead sensor. However, the sensor can provide warning to substantially reduce the speed at which an obstruction or fouling hazard is encountered, and in some cases the obstruction may be avoided completely.

Promising sensors for guideway integrity, physical security, and 'other' hazards are identified in Tables 3.3.2-1 and 3.3.2-2, which list sensors and other features incorporated into a conceptual architecture for hazard mitigation.

Architecture Assessment for Risk Mitigation

A conceptual architecture was developed which consists of a system-level combination of sensor and non-sensor mitigation methods. The system-level design process minimizes risk and cost through judicious trade-off of mitigation methods, including vehicle/guideway design, sensors, passive means, and operational procedures. The architecture's expected performance was evaluated by comparing the post-mitigation risk estimates against the original, unmitigated system risks. Ten of the original thirty-seven unacceptable risks remained categorized as unacceptable following application of the conceptual architecture. In spite of the mitigations, trespassers, maintenance workers, and suicides will reach the guideway and occasionally be killed. Vandalism and facility crime will be decrease, but not be eliminated. The frequency of fires in vehicles, stations, and along the wayside will be minimized, but deaths will likely occur during the system lifetime. Careful attention to safety throughout the design and implementation process is required to minimize the effect of hazards.

This report considers sensors, information processing, and communications for sensor-based risk mitigation. Non-sensor mitigations methods are addressed to better assess the role of sensors as part of an integrated system of risk mitigation techniques. Figure 1 highlights some characteristics of sensor-based risk mitigation. Three sensor deployment styles are shown: (1) on-vehicle, highlighted by the radiation cone from an active forward-looking sensor; (2) a wayside sensor, identified in the figure as a local sensor, and (3) guideway-mounted sensors, shown as embedded in the guideway. Each of these sensor elements requires both processing of the sensor data and communication of the results to the appropriate location. The processing may be done at the sensor location, at a central facility, at the ultimate destination for the data, or at any combination of the three. Many sensor-to-processor-to-vehicle communications paths are possible. A guideway sensor could communicate directly with maglev vehicles, or communicate with a central facility which could transmit any appropriate information to the maglev vehicle or other systems. In some instances the sensor may communicate with both simultaneously.

Sensor communications needs are examined in the context of an overall maglev control system. A limited operational concept was developed to identify the system elements (e.g., control centers, maintenance centers) that would require sensor data, including operator requirements. This information is used, along with the sensor data characteristics, to derive the preliminary functional communications requirements. Sensor data is characterized and allocated to links in a logical

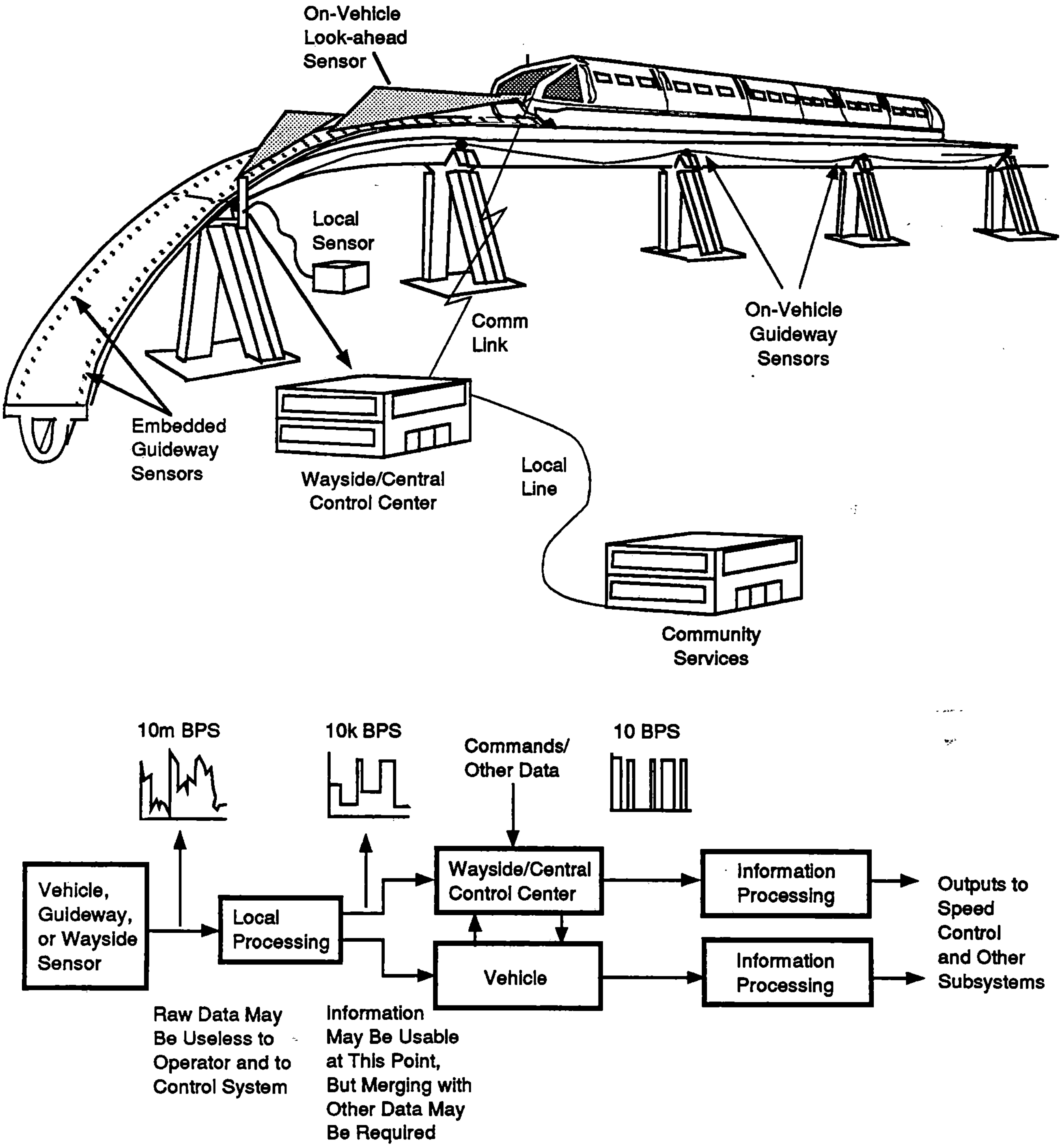

Figure 1 Sensors, Information Processing, and Communications Combine To Meet Requirements

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network among system elements. Sensor data processing needs are assessed to determine appropriate processor locations, relative to the system elements, and to derive the aggregate data transmission requirements.

The sensor communications network consists of a dual-ring, fiber-optic backbone network spanning the length of the guideway and connecting local area networks (LANs) in stations, control centers, the maintenance center, and on the vehicle. The fiber-optic backbone provides high bandwidth and interference immunity. Vehicles will communicate with the wayside through leaky coax or slotted waveguide. The wayside coax or waveguide elements will then be coupled to the fiber-optic backbone at regular intervals.

Technology Development Requirements

New technology research initiatives are suggested based on high-potential sensors having medium or low technical risk. These initiatives include areas that could be categorized as basic research, to areas that could be described as system or application development using proven devices or technology. Sensors that evaluate as high in potential and high or moderate in technical risk for each application are considered. Suggested research initiatives include development of the local line sensors described above, examination of forward-looking on-vehicle sensors, and investigation of a "break-wire" guideway misalignment detection system.

Report Organization

This report is divided as follows. Section 2 summarizes the tasks performed and the associated methodology applied. Section 3 describes the findings of the study. Specifically, subsection 3.1 describes the risks identified, 3.2 describes technical assessment of sensors which might be employed to mitigate hazards, and 3.3 develops and describes a conceptual architecture for risk mitigation which includes sensor and non-sensor mitigation methods, and addresses communications requirements for the maglev system as a whole, as well as for the sensor subsystem. Subsection 3.4 describes technology development requirements. Appendix A provides references, and Appendix B summarizes the identified maglev risks. Appendix C contains sensor merit evaluation tables. Appendix D contains brief descriptions of candidate sensors for detecting obstruction, fouling and guideway integrity hazards.

2.0 TASKS PERFORMED

This study was performed in three phases; the detailed findings of each phase are documented in interim reports.[1,2,3] Figure 2-1 shows the relationship among the three tasks.

2.1 TASK 1 - RISK IDENTIFICATION

A preliminary hazard assessment (PHA) was performed as described by MIL-STD-882B, which outlines a program for system safety. During the current concept exploration phase of the system life cycle, 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 PHA provides an indication of the system risks which should be addressed during system development. At each system life-cycle stage, the hazard analysis is used to recognize those hazards which require . Efforts can be focused on the hazards having the highest risk and severity. These safety analysis iterations encourage evaluation of design options from a safety perspective and will uncover increasingly more subtle hazards.

Recommended probability, severity, and risk categories are provided in Appendix A of MIL-STD-882B. These categories have been modified in previous FRA-sponsored work.[4,5] Table 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 each hazard based on severity and probability values. The relationships among these parameters are listed in Table 2.1-1.

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."[6]

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 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.

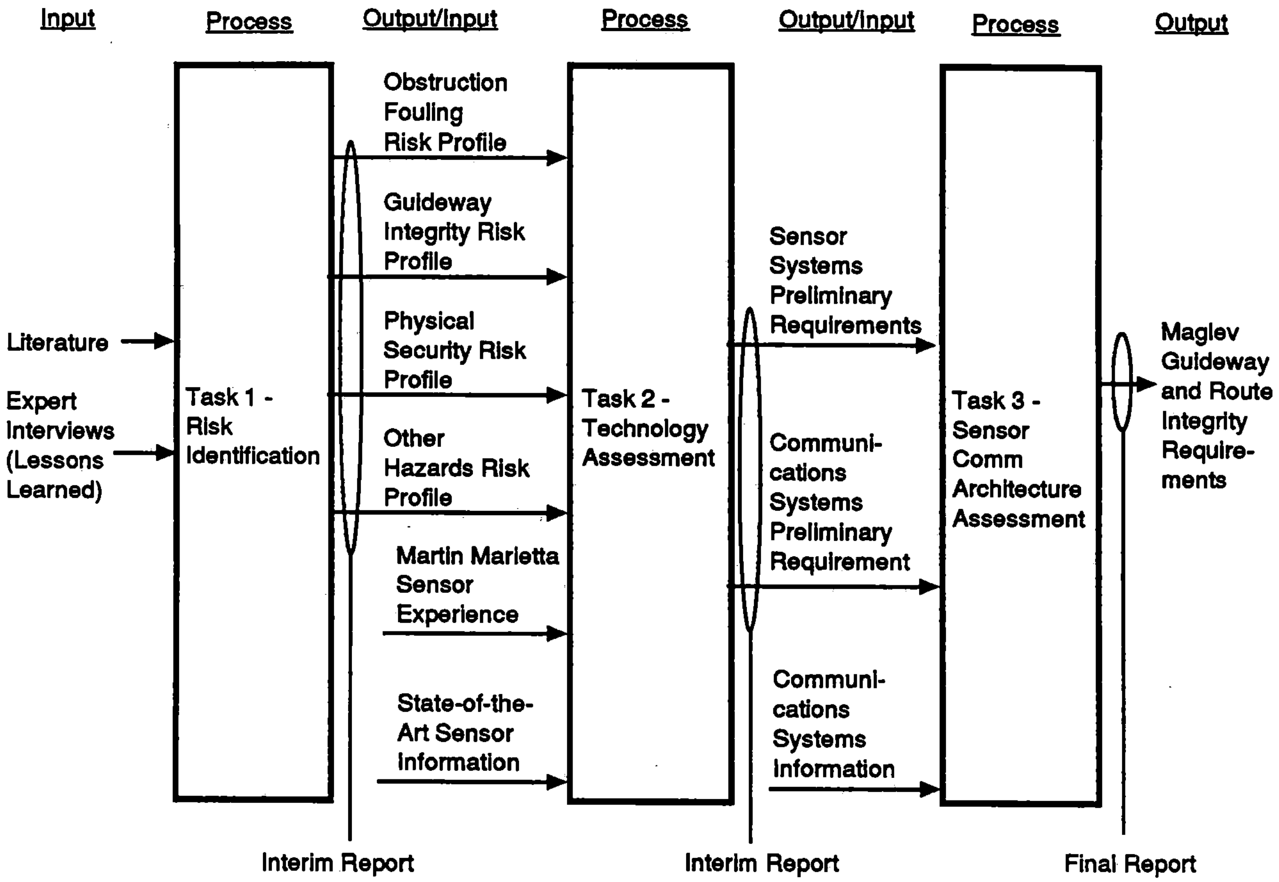

Figure 2-1 Relationship among the Three Tasks

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Table 2.1-1 Probability and Severity Categories and Risk Assessment

Probability and Severity Categories

Frequent -	Not unusual; could occur 10 times annually
Probable -	Could occur 10 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 of individual(s), 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; 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

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

GM1237-1

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 or guideway design. Initially, system designers concentrate on the elimination of the most severe hazards, independent of the hazard frequency.

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 the risk levels assumed by existing transportation systems may reveal appropriate goals for maglev systems.

Assumptions were made in order to assess the existence of hazards and their associated probability and severity. Although advanced maglev prototypes exist, system architecture and component designs for the U.S. are not defined. These assumptions were used to assist the risk identification task:

1) No specific maglev system design;
2) More than 90% of the guideway elevated 3m or more above ground;
3) Maximum speed of 134 m/s in most analyses, with slower speeds around stations;
4) 40-year nominal system life;
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 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.

2.2 TASK 2 - SENSOR TECHNOLOGY ASSESSMENT

A list of candidate sensor systems was developed for each of the four risk profile categories. The candidates were evaluated based on potential applicability as judged against the evaluation criteria described in this subsection.

Evaluation criteria were established to focus the selection of candidate sensors. The basis for these criteria included the risk profiles and the limited maglev system assumptions used to define hazards and assign risk values. Candidate sensors were evaluated with respect to each hazard and assessed in terms of applicability and technological risk.

A rating of the potential of each sensor technology for mitigating specific hazards and an assessment of technological maturity is provided in Appendix C.

2.3 TASK 3 - SENSOR COMMUNICATIONS ARCHITECTURE ASSESSMENT

A conceptual architecture is developed which combines the complementary use of sensor and non-sensor mitigation methods. The architecture employs selected sensors, passive measures, design features, and operational procedures to mitigate hazard risk. A preliminary deployment configuration is developed to determine appropriate communications network requirements for connection of the sensors and control elements of the maglev system.

The risk reduction attributable to the features of the conceptual architecture is shown by means of a reassessment of the original risk profiles. The risk assigned to each hazard is examined for reduction in the severity and probability assessments. A reduction in either assessment could yield the assignment of a reduced value of risk.

A basic maglev system operational concept was developed to identify the system elements, such as control centers, vehicles, guideway, maintenance centers and wayside facilities, that would require data obtained from sensors. Preliminary functional communications requirements were developed from the operational concept and the resulting system data flows to provide a foundation for the sensor communications architecture. Sensor data was then further described and allocated to links in a logical network between system elements.

Selection of appropriate communications performance requirements is as critical to the success of a maglev system as the selection of functional requirements. Data rates and delay time requirements were identified. The selected delay times for sensor data must support top-level performance requirements. Sensor data processing needs were assessed to determine appropriate processor locations, and to derive the aggregate data transmission requirements. Search of the communications literature helped assess functional data needs and potential communications solutions. These functional needs included, for example, the functions identified by the Advanced

Train Control System for locating, identifying, and controlling vehicles. These functional needs have been reflected in the derived preliminary functional requirements.

Network topologies and communications link types were selected following establishment of sensor locations, sensor data processing locations, data destinations, and other requirements.

3.0 FINDINGS

3.1 RISK IDENTIFICATION

Existing transportation modes operate with fatalities and have implied risk assignments of "acceptable with management review." (See Table 2.1-1) U.S. automobile accidents cause 50,000 deaths per year.[7] Automobile risks are not an appropriate reference for maglev transportation risks because automobiles are not operated by sanctioned employees. 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 [7] 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.). 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.

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. MIL-STD-882B methodology calls for the hazard severity to be "a qualitative measure of the worst credible mishap." The risk assignments in this study conservatively assume that the risk will not be mitigated, except when it appears obvious that standard design or construction techniques will be adequate. Hazard probability and severity characterizations presumes good standard design practices, but no special mitigation techniques. Tables 3.1-1 through 3.1-4 list the maglev hazards identified, along with their estimated severity, probability, and risk. Appendix B briefly describes each hazard.

Table 3.1-1 Obstruction and Fouling Hazards

Hazard	Risk	Severity	Probability
Large or heavy objects thrown from above guideway	Unacceptable	Catastrophic	Frequent
Trespassers	Unacceptable	Catastrophic	Frequent
Impinging cars and trucks	Unacceptable	Catastrophic	Probable
Large animals on guideway	Unacceptable	Catastrophic	Probable
Rock falls, debris, limbs on guideway	Unacceptable	Catastrophic	Probable
Fouling by vehicle on adjacent track or guideway	Unacceptable	Catastrophic	Probable
Maintenance personnel on guideway	Unacceptable	Catastrophic	Probable
Suicides	Unacceptable	Catastrophic	Probable
Train at unknown or wrong location	Unacceptable	Catastrophic	Probable
Other vehicles intentionally on guideway	Unacceptable	Catastrophic	Probable
Objects hung above guideway	Unacceptable	Critical	Frequent
Train component falls on guideway	Unacceptable	Critical	Probable
Snow, ice, standing water	Unacceptable	Critical	Probable
Extreme hail, rain, and lightning	Unacceptable	Critical	Probable
Dirt and mud	Unacceptable	Critical	Probable
Projectiles	Unacceptable/Decision required	Marginal	Occasional
Small rocks, bottles, tools etc. on guideway	Acceptable with review	Negligible	Frequent
Small animals on guideway	Acceptable with review	Negligible	Frequent
Magnetic materials	Acceptable with review	Negligible	Frequent
High winds, tornadoes, microbursts	Acceptable with review	Negligible	Frequent

Table 3.1-2 Guideway Integrity Hazards

Hazard	Risk	Severity	Probability
Misaligned joints	Unacceptable	Catastrophic	Frequent
Series of misaligned joints	Unacceptable	Catastrophic	Frequent
Guideway switch failure	Unacceptable	Catastrophic	Probable
Switch indication failure	Unacceptable	Catastrophic	Probable
Earthquake	Unacceptable	Catastrophic	Probable
Washout	Unacceptable	Catastrophic	Probable
Missing or severely misaligned guideway section	Unacceptable	Catastrophic	Occasional
Distortion of guideway	Unacceptable	Critical	Frequent
Separation of rails from guideway structure	Unacceptable	Critical	Probable
Guideway components mis-installed or vibrate out of place	Unacceptable	Critical	Probable
Aging of components	Unacceptable	Critical	Probable
Effect of emergency landing skid use on guideway	Unacceptable/Decision required	Marginal	Probable

Table 3.1-3 Physical Security Hazards

Hazard	Risk	Severity	Probability
Vandalism	Unacceptable	Catastrophic	Frequent
Bullets	Unacceptable	Critical	Frequent
Station crime	Unacceptable	Marginal	Frequent
Security of support facilities	Unacceptable	Marginal	Frequent
Terrorism	Unacceptable /Decision required	Catastrophic	Remote
Right-of-way violation by trespassers	Acceptable with review	Negligible	Frequent

Table 3.1-4 "Other" Hazards

Hazard	Risk	Severity	Probability
Hazardous material leaking from adjacent pipeline or from vehicles on shared right-of-way	Unacceptable	Catastrophic	Probable
Vehicle fire	Unacceptable	Catastrophic	Probable
Embedded software control error	Unacceptable	Catastrophic	Probable
Human factors induced accident	Unacceptable	Catastrophic	Probable
Wayside fire	Unacceptable	Catastrophic	Probable
Unrestrained passengers	Unacceptable	Catastrophic	Probable
Guideway fire	Unacceptable	Catastrophic	Occasional
AC power grid failure	Unacceptable/Decision required	Marginal	Probable
High-speed clamp-on	Unacceptable/Decision required	Marginal	Probable
Operator-less train	Acceptable with review	Negligible	Probable

3.2 TECHNICAL ASSESSMENT - RISK MITIGATION MEASURES

This section summarizes the identification, characterization, and evaluation of potential sensors for mitigating maglev risks. Sensors are one possible risk mitigation measure. Sensor technology could conceivably be deployed to mitigate all hazards, but such a solution would be complex and expensive. A judicious combination of sensor and non-sensor mitigation methods, described in subsection 3.3, will likely be used in maglev systems. Non-sensor methods include vehicle guideway design, operational procedures, and passive mitigation approaches.

3.2.1 Candidate Sensor Selection

The suitability of specific sensor technologies depends on performance, cost, maturity, and adaptability to environmental conditions. Maintenance requirements throughout the system life cycle are an important consideration in the selection of individual sensor technologies and deployment options.

Sensors will be subject to harsh environmental conditions, including cooling, heating, and humidity cycles; dirt, dust, and other wind-blown abrasives; and coating by natural and industrial pollutants. Accumulation of foreign material, including dirt, rain, snow, and ice, will impact the performance of some sensor technologies more than others. Optical sensors, for example, may be very sensitive to this accumulation and may require special design or maintenance measures to ensure operational viability. The maglev system itself may adversely impact vehicle- and guideway-mounted sensors. These effects include induced vibrations and magnetic fields; the moving vehicle's quasi-static magnetic fields result in varying magnetic fields at nearby sensors. This changing magnetic field can induce unwanted electrical currents in the sensor components and network wiring. Similarly, maglev systems employing guideway stator coils will induce extraneous currents.

Candidate sensor technologies for risk mitigation are listed in Table 3.2.1-1. Candidate sensors were identified through knowledge of the risk profiles and the assumptions about the system concept. Reference 2 contains a characterization table for each sensor which includes such information as deployment, data rates, advantages, disadvantages, limitations, cost, maturity, and associated safety hazards. Appendix D briefly describes the obstruction and fouling and guideway integrity sensors listed in Table 3.2.1-1. Each sensor technology is described in greater detail in reference 2.

Table 3.2.1-1 Candidate Sensors Identified in Each Risk Profile Category

Obstruction and Fouling	**Guideway Integrity**	**Physical Security**
-Microwave Radar -Millimeter Microwave Radar* -Laser Radar -Infrared Imaging -Visible Imaging -Local Guideway Line Sensors* -Physical Intrusion Cable -Canary Car -Beacons* -Frangible Rods -Upward-Pointed Beam -Anemometers -Acoustics	-Fiber Optic -Acoustic -Computer Vision Guideway Inspection -Seismic* -Built-in-Test Equipment* -On-Vehicle Vibration Sensor -Break Wire* -Differential GPS-Based Guideway Geometry Measurement -Guideway Geometry Car -Surveillance Camera	-Standard Surveillance Cameras* -Computer Vision* -Door Alarms* -Tamper Alarms* -Fire Alarms* -Emergency Buttons* -Faux Electronic Surveillance* **"Other" Hazards** -Hazardous Vapor -Infrared Fire Detector -Pipeline Leak Detector -Dead-man Detector

* - Sensors included in conceptual architecture

Candidate sensors were evaluated with respect to each hazard within the risk profiles and assessed in terms of applicability and technological risk. These assessments are summarized in Appendix C. The evaluation criteria were developed from the risk profiles and the assumptions about the system concept. New hazards and associated risks will be introduced as the maglev system design evolves; these must be identified and mitigated throughout the development life-cycle by disciplined and recurrent safety analysis and design iterations. The most promising sensor technologies and deployments are marked in Table 3.2.1-1 with an asterisk and are included in the conceptual architecture described in subsection 3.3.

3.2.2 Sensor Evaluation

Tables 1 through 4 of Appendix C list maglev risks and rate candidate sensors which possess mitigation potential for the hazards. Items which present a similar signature to the sensor system are grouped together. For example, some previously identified obstruction and fouling hazards have been grouped together since they are not distinct from a sensor detection viewpoint; a maintenance worker and a trespasser are identical when viewed by look-ahead sensors. For passive mitigation, it matters how the obstructions got there, but for sensors, only that they are there.

Processing of look-ahead sensor data is as important as the sensor itself. In the maglev environment, conventional processing techniques may produce high detection rates at the expense of high false-alarm rates. The obstruction or fouling signal will often be buried in the signals due to nearby but harmless objects. Techniques to handle normal changes in measured signature due to benign effects, such as normal snow accumulation or rain wetting, will be required. A high false alarm rate is possible even when combining information from the best sources. Sensor system developers will expend substantial effort developing algorithms or techniques to discriminate between benign sensor signal characteristics and the features which indicate obstruction or fouling. Every characteristic of the hazard detection challenge must be examined and exploited to extract the information needed to make an obstruction/fouling decision.

3.2.2.1 Environmental Factors for Obstruction and Fouling Sensors

Many environmental factors can degrade sensor system performance. Heavy rain can severely attenuate all but the lower microwave frequencies. Fog, and falling snow attenuate millimeter microwave, infrared, and optical signals. Humidity levels can strongly affect some frequencies. Echoes from precipitation compete with the obstruction and fouling echoes.

Other environmental effects can adversely impact forward-looking sensor performance. Heat shimmer, and abnormal changes of the index of refraction with height can disrupt hazard detection, depending on the type and deployment of the sensor. The sun is a significant microwave, infrared, and optical source. Direct sun or its reflection can temporarily blind or degrade sensor performance. Finally, sensor windows can be clogged by rain, ice, snow, and mud.

3.2.2.2 Deployment of Forward-Looking Obstruction and Fouling Sensors

None of the vehicle-mounted, forward-looking systems will detect objects at the maximum ranges required at the maximum operating speed due to line-of-sight limitations. However, some of these sensors can detect obstructions at lesser ranges and thus avoid hitting objects at full speed, or perhaps not at all, when emergency braking is used.

Wayside sensors, when located to the side of the guideway, will not be appropriately sited to detect some hazards, notably fouling from an adjacent or shared right-of-way. These sensors can detect the vehicle from the wayside, but the viewing geometry would be unacceptably poor. Sensors located between the shared right-of-way may do better, but their range would be severely limited at some sites by curved track or guideway. Also, sensors mounted between shared right-of-ways are themselves subject to damage by the fouling vehicle.

An ideal obstruction and fouling sensor might be a narrow sensing "line" in space which probes the maglev operational envelope. Infrared and light beams over short distances, for example several guideway sections (100 meters), are line sensors because their narrow beamwidths approximate a line-in-space over these short distances. Lines are narrow compared to the operational envelope and thus are not affected by false targets a short distance away. The sensor system might use small, low-power transmitters every one to four guideway sections. Guideway section lengths may be from 25 to 100 meters. Receivers would be placed at the same intervals. The challenge is detecting true obstructions or fouling, while rejecting false targets, and doing this at low cost. The low cost is important because this method of instrumenting the operational envelope would use many sensors. Likewise, the large number of sensors present means that the false-alarm rate for individual sensors must be held very low if the entire system is to have an acceptably low sensor false-alarm rate.

3.3 SENSOR COMMUNICATIONS ARCHITECTURE ASSESSMENT

This section describes a conceptual architecture that incorporates sensor and non-sensor based mitigation strategies. Figures 3.3-1 and 3.3-2 list the sensor and non-sensor features which have been selected for incorporation into the architecture. Individual techniques are identified by letter and number; e.g., A-1 is "Guideway stanchions withstand car/truck collisions." These reference numbers are used in subsection 3.3.3 where architecture risk mitigation performance is discussed.

3.3.1 Operational Concept and Assumptions

Control centers will be used to control all system operations. Redundant control centers will minimize the possibility that failure of a control center will disrupt operations. Each control center receives all system data and can perform all system functions, but only one control center is in command at any one time. The control center schedules the vehicles and generally controls them, e.g., setting start times, issuing start commands and maximum speed commands. Vehicles may stop of their own accord as they note hazards, experience vehicle failures, or otherwise require slowing or stopping.

A maintenance center will receive maintenance messages and request maintenance data from the vehicles and guideway. The maintenance center may be stand-alone or incorporated into one of the control centers, but is functionally separate from the control centers.

The system will incorporate high- and low-speed switches. Both on-line and off-line maglev stations will be used. Single guideway was considered in the estimates, but if traffic between city pairs is expected to be heavy, or to meet system availability requirements, dual guideway will likely be used. This will double the relevant communications loads.

Up to 20 maglev consists may be in operation traveling in the same direction at any one time. Two trains may sometimes occupy the same sector through mistake, accident, special operational considerations, or when a "dead" vehicle recovery is in progress; these events will be considered irregular. This implies a requirement for the communications system to communicate with multiple vehicles in the same sector.

Additional assumptions about the system implementation and operation were made to obtain estimates for the aggregate data requirements among system elements. It was assumed that the total length of guideway covered by the sensor network is 400 km, and that local guideway line sensors will be installed at 100 meter intervals along one-half the length of the guideway. One-half of the guideway is assumed to have a very low probability of obstruction, and thus not require local obstruction sensors. The control center receives all data from all local guideway line sensors continuously. The same data is sent directly to each vehicle, for sensors up to 20 km ahead of the vehicle.

The system is assumed to incorporate two seismic sensors. These locations may be near the guideway or not, as dictated by design considerations. Any specific maglev implementation may contain no seismic sensors, or more than the two used here, depending on the local seismic risk and size of the system.

Built-in-test equipment is assumed in each sensor in the system and in five other pieces of equipment present in each consist. The guideway is assumed to possess one piece of built-in-test equipment (e.g., built-in-test equipment associated with switches) for every 5 kilometers.

3.3.2 Selection and Placement of Sensors and Other Mitigation Techniques

Mitigation features of the architecture are listed in Tables 3.3.2-1 and 3.3.2-2. Identification of sensor-based hazard mitigation was a focus of this study. However, the architecture's non-sensor mitigation methods are described first, since non-sensor methods will be the first line of defense against hazards.

Hazard Mitigation by Passive Features. The frequency of encountering a large object hazard will be substantially reduced by use of elevated guideway over 90 per cent of the maglev route. Reference 8 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 reduce the surface area suitable for resting objects.

Fences will protect all at-grade-level guideway segments. Fencing and/or screening will be used to protect the guideway from objects thrown, fallen, or hanging from overhead bridges and buildings. Ditches, walls, and distance will be used singly, or in combination, to reduce the risk of encroachment from rail vehicles on a shared right-of-way. Similar barriers, plus jersey barriers, will be used to reduce the incidence of intruding vehicles from shared roadways.

Table 3.3.2-1 Obstruction/Fouling and Guideway Integrity Risk Mitigation Methods

A. Vehicle/Guideway Design
1) Guideway stanchions withstand car/truck collision
2) Tolerate small objects, including projectiles
3) Withstand substantial snow, ice, rain, mud
4) Withstand highest normal winds, minimal damage shutdown in higher winds
5) Minimal damage due to largest hail
6) Tolerant of lightning-induced currents
7) Airbags / rear facing seats / seatbelts available
8) Controlled crushing of vehicle to withstand hitting humans, large animals, medium objects
9) Maximize required vehicle/guideway alignment tolerances
B. Passive Mitigation
1) 90% raised guideway
2) Fencing/screening near overhead bridges, buildings
3) Ditches, walls, distance between shared rail/guideway
4) Jersey barriers, ditches, walls, distance between shared roadway/guideway
5) Fence around grade-level guideway
6) Construction/installation quality and design quality
7) Lighting protection
8) Cleared space between guideway and surrounding terrain
9) Means for quick egress from guideway
C. Sensor Mitigation
1) Guideway local line sensor
2) MMW forward-looking sensor on vehicle
3) Beacons
4) On-vehicle vibration sensing
5) Guideway alignment - real-time gross misalignment detection (break wire)
6) Geometry/Inspection vehicle
- automated visual inspection
- vehicle vibration
- differential GPS track geometry
7) Guideway alignment trends
- real-time in place monitoring
8) Seismic sensor
9) Built-in-Test Equipment
10) Monitoring of bad control sensor data
D. Operational Procedures
1) Inspect/clean control system sensors
2) Maintenance personnel/construction sites always notify control center of activities and receive confirmation
3) System will slow/stop on high vibration levels

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Table 3.3.2-2 Physical Security and "Other" Risk Mitigation Methods

A. Vehicle / Guideway Design
1) Hardware or redundant systems and / or coding to protect against run-away software
2) Employ fire resistant materials
3) Design gracefully tolerates AC power grid failure
4) Clamp-on avoidance / minimal impact if occurs
5) Bullet protection for guideway/vehicle
6) Fire extinguisher system on-board
B. Passive Mitigation
1) Locates facilities in lower crime area
2) Fences
3) Lighting
4) Bullet barriers for personnel / facilities
5) Routing to avoid hazardous pipelines
6) Armored / specially sealed pipeline sections
7) Fire extinguisher for facilities
C. Sensor Mitigation
1) Surveillance cameras with computer vision
2) Faux surveillance cameras
3) Emergency buttons
4) Fire alarms
5) Tamper alarms
6) Door alarms
7) Pipeline leak detection
D. Operational Procedures
1) Guard patrols
2) Facility inspections
3) Human factors input to influence system design, operation, and training
4) Clear wayside of excessively flammable debris

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The vehicle and guideway will be designed to tolerate or receive minimal damage from some hazards. Guideway stanchions will withstand most car and truck collisions, while continuing to provide acceptable alignment tolerances and other required guideway services. Vehicle/guideway clearances will allow the vehicle to clear small objects; or ensure that the objects are ejected harmlessly from the system, or both. The vehicle will sustain negligible damage from small projectiles, including small birds, rocks, and bullets.

The vehicle/guideway combination will withstand normal amounts of snow and ice expected during operation. Operational procedures may call for snow/ice removal as a result of major snowfalls. The combination will withstand the highest normal winds and will permit reduced-speed operation, including shutdown, with minimal damage if the highest expected wind conditions are exceeded. The vehicle will receive minimal damage due to the largest hail encountered at full operational speed. The guideway will not be damaged by hail.

Seat belts will be available for use, but not required. Rearward facing seats may be used to reduce the possibility of injury in the event of rapid decelerations. Air bags may be used if found suitable.

<u>Sensor Mitigation Features.</u> Sensors were selected to mitigate those hazards which could not be fully mitigated by the passive methods described above. The sensors shown in Tables 3.3.2-1 and 3.3.2-2 result from analysis of risk mitigation trade-offs between vehicle/guideway design solutions, passive features (e.g., fencing), and operational procedures.

Local very-short-distance guideway section-by-section line sensors would be employed along much of the route. These sensors would employ narrow infrared, visible light, or MMW transmitters at one end of a section of guideway beam, and a corresponding receiver at the other end of the section of beam to detection obstruction and fouling hazards. Such sensors might not be employed along long straight sections of route where the on-vehicle sensor would provide its best performance. Local sensors would be the sole obstruction and fouling sensor for some route segments.

A millimeter microwave (MMW) radar is included in the architecture for use on the vehicle as a forward-looking obstruction sensor. The MMW sensor will not detect obstructions or fouling in time to allow a "normal" stopping rate to be used. Hills, valleys, curves, and the normal earth curvature severely limit an on-vehicle look-ahead sensor. However, the sensor can provide warning to substantially reduce the speed at which an obstruction or fouling hazard is encountered, and in some cases the obstruction may be avoided completely. An on-vehicle, look-ahead sensor offers value as the last line of defense against obstruction or fouling not otherwise prevented or detected.

The architecture also includes beacons on the vehicles, and vibration sensors. The beacons are one measure to detect other nearby maglev vehicles. Beacons can be effective for detecting trains at unknown or wrong locations. They can be used to warn maintenance personnel and construction sites. The maglev control system would be cognizant of work sites and all vehicle locations. If unexpected beacon returns were detected, the control system would be alerted and the vehicle stopped.

Vibration sensing on the vehicles could be used for multiple purposes. Excessive vibration might be due to very high winds, misaligned guideway, or vehicle failure. The system could be designed to slow or stop vehicles upon detection of excessive vibration. Guideway section-to-section alignment errors and guideway distortions may be detectable through use of on-vehicle low frequency vibration sensors. Relative beam lateral displacements of perhaps a few millimeters will have to be detected at the inter-beam boundaries. Guideway distortions may be detectable in the same manner. This method will easily detect and record the location of severely misaligned beams. It is possible that this method will be able to detect the separation of rails from the guideway structure, depending on the system design selected and on the resulting characteristics of separated rails.

3.3.3 Communications

Figure 3.3.3-1 illustrates an architecture for communicating maglev sensor data. The architecture comprises a selected set of network topologies and communications link technologies. The link technologies were selected based on required link lengths, bandwidths, and their general robustness. There are three link categories: vehicle-to-wayside, wayside-to-control center, and vehicle direct-to-control center.

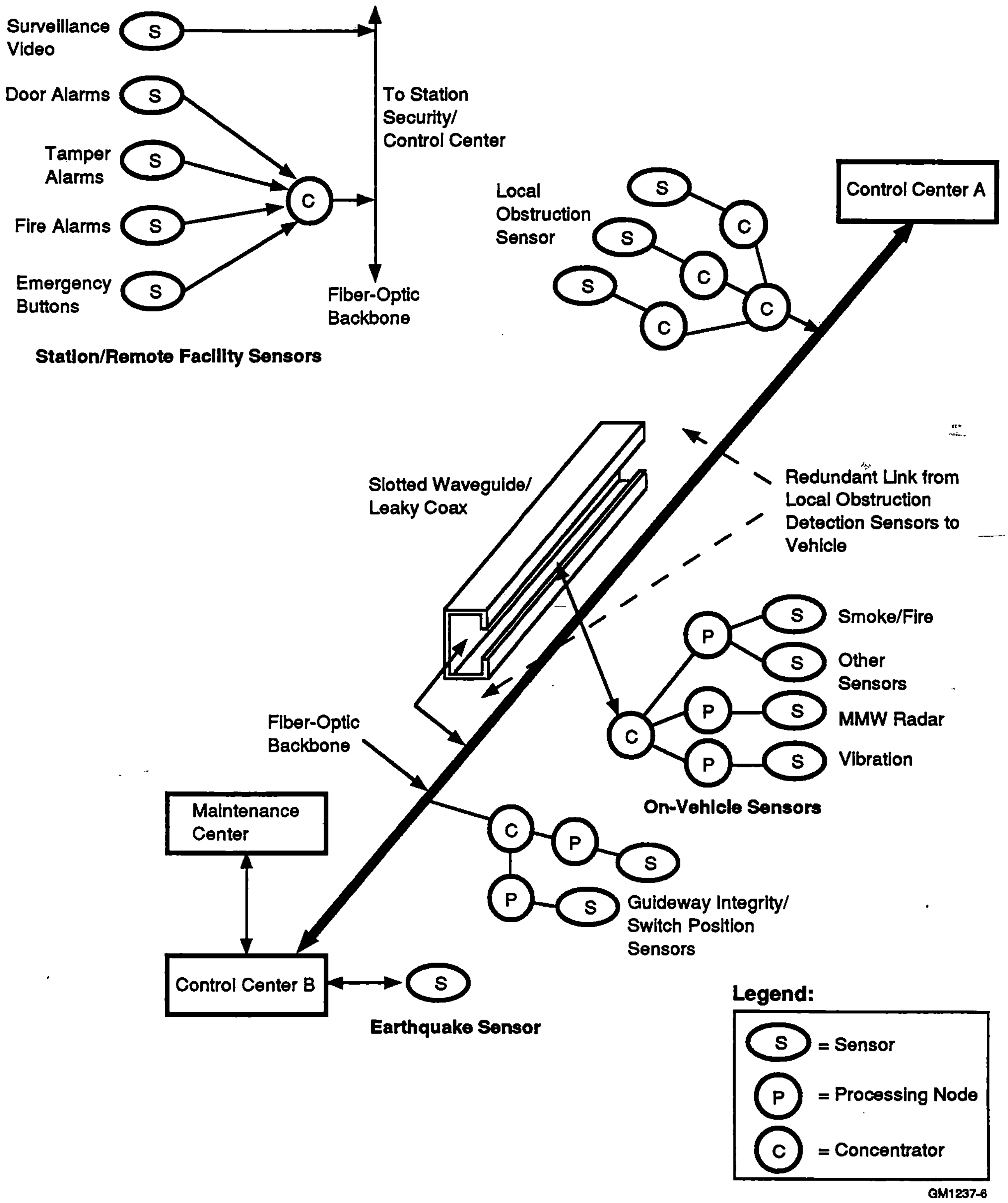

Figure 3.3.3-1 Conceptual Sensor Communications System Architecture

The architecture is intended to meet the following preliminary functional communications requirements which were identified during the study:

1) Support limited autonomous operation of maglev vehicles;
2) Support central control of vehicle operations;
3) Transmit and deliver sensor data to end destinations;
    a) Vehicle and control center commands to individual sensors;
    b) Maintenance data from sensor to maintenance center;
    c) Sensor "conditioning" data from the maintenance or control center;
5) Identify individual sensors;
6) Support redundant means to ensure delivery of safety-critical data;
7) Provide reliability and availability consistent with overall system operations;
8) Support delivery precedence of operational data and commands.

At the system level, the architecture incorporates a high-capacity backbone structure. The selected backbone is a dual fiber-optic ring extending the length of the guideway to the control centers and the maintenance center. Repeaters will be required at 10 to 25 km intervals. Continued development of low-attenuation fibers and signal-processing components will increase this interval. Fiber-optic technology was selected because of its very high bandwidth, immunity to interference, ease of installation, low-cost, and maturity.

Vehicles will communicate with the wayside through leaky coax or slotted waveguide. The wayside coax or waveguide elements will then be coupled to the fiber-optic backbone at regular intervals. Leaky coax or slotted waveguide was selected over the nearest contender, microwave or millimeter microwave transmissions from the wayside; However, this is an area for further research. Taps at periodic intervals connect the slotted waveguide or leaky coax to the backbone.

Periodic taps attached to the backbone will inject obstruction and fouling sensor information into the backbone, and will receive sensor commands and data from the control system. Concentrators will combine data streams from groups of sensors before providing the data to the backbone. The communications load from the local guideway obstruction and fouling sensors may be reduced by commanding sensors not in the immediate path of the vehicle to stop data transmissions. Each sensor will send and receive maintenance data in addition to the sensor data. As noted previously, some system design philosophies would separate safety and maintenance data. System analysis will be required to determine the most cost-effective approach to meeting all requirements.

Obstruction and fouling and guideway integrity sensor data will be processed locally, so the data rates will be low. High-bandwidth data transmission requirements are required for physical security systems located in stations and in remote or unattended facilities. Security monitor data will primarily be viewed at the local site. However, personnel will not always be available locally to monitor the surveillance data. Accordingly, the control system will select a small number of cameras to send video to the control centers.

3.3.4 Expected Performance of the Conceptual Architecture

Tables 3.3.4-1 through 3.3.4-4 show the originally identified hazards, the original risk assessments, mitigation methods that the proposed architecture applies to each hazard, and the expected risk values following mitigation. The codes for the mitigation methods are defined in Table 3.3.2-1.

In most instances the risk category has been substantially reduced, as expected. Sometimes the assessed risk level has not changed. This is because the probability, severity, and risk definitions are broad and conservative. One example of this is the "Fire in vehicle" hazard in Table 3.3.3-4. Without mitigation, it was estimated that a vehicle fire might occur ten times in the maglev system lifetime (probable). Following mitigation we estimated that this will occur at least once (occasional). The severity is the same (catastrophic) with or without mitigation since a death can easily result from any fire in a closed space. The risk associated with any hazard which is probable or occasional and which is potentially "catastrophic" is "unacceptable". Thus no risk mitigation appears to have occurred. This is only an appearance, however, because of the conservative risk categorization. Unmitigated, there may have been ten fires and five deaths. Mitigated there may be only one fire and one death, which would remain catastrophic, but an improvement.

Ten of the original thirty-seven unacceptable risks remain categorized as unacceptable following application of the conceptual architecture. In spite of the mitigations applied, trespassers, maintenance workers, and suicides will reach the guideway during the life of the system and occasionally be killed. Vandalism, and station and support facility crime, will be decreased by the suggested mitigation measures, but not eliminated. The incidence of fires in vehicles, stations, and along the wayside will be minimized, but as noted above, deaths will likely occur sometime during the system lifetime. Finally, death of an unrestrained passenger can be expected sometime during the life of the system.

Table 3.3.4-1 Obstruction and Fouling Post-Mitigation Risk Improvement

Hazard	Unmitigated		Mitigation Methods	Mitigated	
	Risk	Severity Probab.		Risk	Severity Probab.
Large or heavy objects thrown from above guideway	Unacceptable	Catastrophic Frequent	A-7; B-1,2; **C-1,2**	Un./ dec. req.	Marginal Probable
Trespassers	Unacceptable	Catastrophic Frequent	A-8; B-1,2,5,9; **C-1,2**	Unacceptable	Catastrophic Probable
Impinging cars and trucks	Unacceptable	Catastrophic Probable	A-1,7; B-1,4; **C-1,2**	Un./ dec. req.	Critical Occasional
Large animals on guideway	Unacceptable	Catastrophic Probable	A-8; B-1,2,5,6; **C-1,2**	Un./ dec. req.	Marginal Probable
Rockfalls, debris, limbs on guideway	Unacceptable	Catastrophic Probable	A-2,7; B-1,5,6; **C-2**	Un. / dec. req.	Marginal Probable
Fouling by vehicle on adjacent track or guideway	Unacceptable	Catastrophic Probable	A-7; B-1,3; **C-2,5**	Un./ dec. req.	Catastrophic Remote
Maintenance personnel on guideway	Unacceptable	Catastrophic Probable	A-8; B-9; **C-1,2,3**; D-2	Unacceptable	Catastrophic Occasional
Suicides	Unacceptable	Catastrophic Probable	A-8; B-1,2,5,9; **C-1,2**	Unacceptable	Catastrophic Probable
Train at unknown or wrong location	Unacceptable	Catastrophic Probable	A-7; **C-1,2,3**; D-1	Un./ dec. req.	Catastrophic Remote
Other vehicles intentionally on guideway	Unacceptable	Catastrophic Probable	A-7, 8; B-1,4,5; **C-1,2**	Un./ dec. req.	Critical Occasional
Objects hung above guideway	Unacceptable	Critical Frequent	A-2,5,8; B-1,2,8; **C-1,2**	Un./ dec. req.	Marginal Probable
Train component falls on guideway	Unacceptable	Critical Probable	A-2,7,8; **C-1,2**	Un./ dec. req.	Marginal Occasional
Snow, Ice, standing water	Unacceptable	Critical Probable	A-3,7; **C-1,2**	Acc. w/ rev.	Negligible Probable
Extreme hail,rain, and lightning	Unacceptable	Critical Probable	A-3,4,5,6; B-7	Acc. w/ rev.	Negligible Probable
Dirt and mud	Unacceptable	Critical Probable	A-3; B-1; **C-10**; D-1	Acceptable	Negligible Occasional
Projectiles	Un./dec. req.	Marginal Occasional	A-2; B-2	Acceptable	Negligible Occasional
Small rocks, bottles, tools etc. on guideway	Acc. w/rev.	Negligible Frequent	A-2; B-1,2	Acc. w/rev.	Negligible Frequent
Small animals on guideway	Acc. w/rev.	Negligible Frequent	A-2; B-1,2,5,8	Acc. w/rev.	Negligible Frequent
Magnetic materials	Acc. w/rev.	Negligible Frequent	A-2; **C-1**	Acc. w/rev.	Negligible Frequent
High winds, tornadoes, microbursts	Acc. w/rev.	Negligible Frequent	A-4; **C-4**; D-3	Acc. w/rev.	Negligible Frequent
			Sensor-based mitigation in bold type.		

Table 3.3.4-2 Guideway Integrity Post-Mitigation Improvement

Hazard	Unmitigated		Mitigation Methods	Mitigated	
	Risk	Severity Probab.		Risk	Severity Probab
Misaligned joints	Unacceptable	Catastrophic Frequent	A-7,9; **C-5,6,7**	Un./ dec. req.	Catastrophic Remote
Series of misaligned joints	Unacceptable	Catastrophic Frequent	A-7,9; B-6; **C-5,6,7**	Un./ dec. req.	Catastrophic Remote
Guideway switch failure	Unacceptable	Catastrophic Probable	A-7,8,9; **C-5,9,**10; E-1	Un./ dec. req.	Catastrophic Remote
Switch indication failure	Unacceptable	Catastrophic Probable	A-7; **C-5,9,10;** D-1; E-1	Un/ dec. req.	Catastrophic Remote
Earthquake	Unacceptable	Catastrophic Probable	A-7,9; B-9; **C-1,4,5,8;** D-3	Un./ dec. req.	Marginal Probable
Washout	Unacceptable	Catastrophic Probable	A-7; B-6; **C-5**	Un./ dec. req.	Marginal Probable
Missing or severely misaligned guideway section	Unacceptable	Catastrophic Occasional	A-7; B-6; **C-1,5**	Un./ dec. req.	Catastrophic Remote
Distortion of Guideway	Unacceptable	Critical Frequent	A-9; B-6; **C-4,6,3**	Un./ dec. req.	Marginal Probable
Separation of rails from guideway structure	Unacceptable	Critical Probable	B-6; **C-4,6**	Un./ dec. req.	Marginal Probable
Guideway components mis-installed or vibrate out of place	Unacceptable	Critical Probable	B-6; H-3	Un./ dec. req.	Marginal Probable
Aging of components	Unacceptable	Critical Probable	A-9; B-6; **C-6, C-9**	Un./ dec. req.	Marginal Probable
Effect of emergency landing skid use on guideway	Un./dec. req.	Marginal Probable	B-6; **C-6**	Un./ dec. req.	Negligible Occasional
			Sensor-based mitigation in bold type.		

Table 3.3.4-3 Physical Security Post-Mitigation Risk Improvement

Hazard	Unmitigated		Mitigation Methods	Mitigated	
	Risk	Severity Probab.		Risk	Severity Probab.
Vandalism	Unacceptable	Catastrophic Frequent	E-2,5; F-1,2,3,4; **G-1,2,3,4,5,6**; H-1,2	Unacceptable	Critical Frequent
Bullets	Unacceptable	Marginal Frequent	E-5; F-4	Acc. w/rev.	Negligible Frequent
Station crime	Unacceptable	Marginal Frequent	F-1,2,3,4; **G-1,2,3,5,6**; H-1	Unacceptable	Marginal Frequent
Security of support facilities	Unacceptable	Marginal Frequent	F-1,2,3,4; **G-1,2,4,5,6**; H-1,2	Unacceptable	Marginal Frequent
Terrorism	Un./dec. req.	Catastrophic Remote	E-5; F-2,3,4; **G-1,2,3,4,5,6**; H-1,2	Un./ dec. req.	Catastrophic Remote
Right-of-way violation by trespassers	Acc. w/rev.	Negligible Frequent	B-1,2,5; F-2,3; **G-1,2,6**	Acc. w/rev.	Negligible Frequent
			Sensor-based mitigation in bold type.		

Table 3.3.4-4 'Other' Post- Mitigation Risk Improvement

Hazard	Unmitigated		Mitigation Methods	Mitigated	
	Risk	Severity Probab.		Risk	Severity Probab
Hazardous material leaking from adjacent pipeline or from vehicles on shared right-of-way	Unacceptable	Catastrophic Probable	F-5,6; **G-7**	Un./ dec. req.	
Vehicle fire	Unacceptable	Catastrophic Probable	E-2,6; F-7; **G-4**	Unacceptable	
Embedded software control error	Unacceptable	Catastrophic Probable	E-1	Un./ dec. req.	Critical Occasional
Human factors induced accident	Unacceptable	Catastrophic Probable	H-1	Unacceptable	
Wayside fire	Unacceptable	Catastrophic Probable	B-8; F-5,7; **G-4**; H-4	Unacceptable	Critical Probable
Unrestrained passengers	Unacceptable	Catastrophic Probable	A-7	Unacceptable	Catastrophic Occasional
Guideway fire	Unacceptable	Catastrophic Occasional	B-9, E-2; F-7; **G-3,4**	Un./ dec. req.	Critical Occasional
AC power grid failure	Un./dec. req.	Marginal Probable	E-3	Acc. w/ rev.	Negligible Probable
High-speed clamp-on	Un./dec. req.	Marginal Probable	A-7; E-4	Un./ dec. req.	Marginal Probable
Operator-less train	Acc. w/rev.	Negligible Probable	D-4	Acc. w/rev.	Negligible Probable
			Sensor-based mitigation in bold type.		

3.4 RESEARCH NEEDS

Many research areas exist in the application of sensor technology to maglev systems. These include areas that could be categorized as basic research through a continuum to areas that could be described as system or application development using proven devices or technology. The approach taken in this study contract concentrates on those research areas directly evident from the suggested applications in the conceptual architecture. Also, sensors that are evaluated as high in potential and high or moderate in technical risk are considered. See Appendix C for sensor merit evaluations. This approach leads to a focused and practical assessment for defining new technology requirements.

Obstruction and fouling hazard detection systems will require substantial research and development before a reliable, effective obstruction and fouling detection system can be deployed. Selection of the optimum sensors and sensor configurations for maglev will require careful examination of potential sensor performance against requirements and the operating environment. Development of a suitable processing technology to complement the sensor and produce reliable hazard detection represents a substantial challenge.

We recommend that potential vehicle-mounted, forward-looking sensors and associated data processing methods be investigated even though it will not be possible for these sensors to detect hazards at the maximum desired ranges. However, they can be useful as a last line of defense against obstructions

Obstruction and fouling sensing by wayside-mounted or guideway-mounted electromagnetic beams should also receive further investigation. Research needs here include investigation of potential detection reliability and integrity, sensor data processing techniques, and potential for low-cost production, installation, and maintenance. Investigation of guided-wave obstruction detection technology should be conducted.

On-vehicle vibration sensors and their ultimate measurement sensitivity and capability to reliably detect and characterize small guideway misalignments should be investigated. Their capability to detect excessive winds should also be examined. Sensor data processing requirements and techniques, including algorithms and processing rates, should be developed and characterized. Actual guideway alignment tolerance requirements will be required to properly perform this research.

Reliability and integrity of a breakwire (break fiber) guideway misalignment sensor should be investigated. The promise of the breakwire concept should be confirmed, and sample designs developed and characterized.

The guideway geometry car concept should be further explored to determine practical capabilities and to determine which guideway inspection functions could be of most benefit in a guideway geometry car. The practicality of performing guideway geometry car functions, in part or in whole, from revenue service vehicles should be explored.

Investigations should be conducted to establish the best methods for transmitting data between vehicles and the wayside Technologies to be considered include slotted waveguide, leaky coaxial cable, and microwave transmissions to the wayside.

Significant risk reduction will be achieved through non-sensor mitigation. Later trade studies or requirements analyses may conclude that sensor mitigation is necessary to complement mitigation available from vehicle/guideway design, passive mitigation, and operational procedures. Investigations of the most promising sensors and processing technologies should continue so that they are available when needed, and capabilities and drawbacks are well understood.

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APPENDIX B. IDENTIFIED MAGLEV RISKS

Obstruction and Fouling Hazards. The vehicle can stop safely without disrupting passenger activity using a comfortable deceleration of 0.1g. This will require 9 kilometers to reach a full stop from an operational speed of 134 meters per second. 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 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).

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 lightweight train design. The FRA reported that conventional railroads experienced 32 accidents during 1989 due to objects on or fouling the tracks.[9] 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.

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.

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. 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 minimized 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. These objects may be of low density, e.g. a couch, or high, e.g., a rock.

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 that there were 13 accidents in 1989 due to equipment on or fouling the track.[9] 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.

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 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 incorrectly report its 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.

Humans on the Guideway. The risk is to the individuals and to the vehicle. A maglev vehicle could potentially receive nine times the energy from striking a person as a conventional train going one-third the speed of the maglev vehicle. This and 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.

Between 1966 and 1974, 26.7 per cent 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".[10] 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.

During the period 1966-1974, 5,403 trespassers were killed on U.S. rail right-of-ways.[10] (This figure does not include employees or those killed in grade crossing accidents.)

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, in fact, 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 in Europe 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 less than current values experienced in the U.S. rail system.

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 .[11]

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.

Objects Hung above the Guideway. Hazards 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.

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 is 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, which could clog switching mechanisms or guideway expansion joints. Maintenance tools and components forgotten on the guideway may be a significant source of unwanted objects.

Projectiles Projectiles are distinct from the other small object hazards because they affect 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.

Further, objects hit by the train will sometimes be ejected from the guideway at high speeds, and present a hazard to nearby vehicles, persons and property. 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.

Weather Snow and ice can be expected to accumulate on the guideway of maglev systems built in high snow areas. Hazards associated with winter storms include ice sheet and heavy snow buildup on guidance rails and the guideway. Snow and ice removal requirements vary with the guideway shape and the levitation technology and gap selected.

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. Lightning striking the vehicle or guideway could damage either. Power circuits, communications, and control systems could be disrupted temporarily or permanently. System designs must be reviewed for ability to operate under maximum U.S. sustained and gust wind conditions. Local winds are a function of weather systems and thunderstorms and 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 and last from 10 to 30 minutes.

Guideway Integrity Hazards. Loss of guideway integrity occurs when a guideway parameter exceeds a design tolerance value and causes the guideway to fail to provide a system function to within the previously specified range. The guideway performs or supports critical generalized system functions of: (1) physical support, (2) monitoring and control, and (3) power transmission, levitation, propulsion, braking, and guidance.

Guideway integrity may depend on 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.

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

Guideway misalignment 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. 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, i.e. several millimeters. Therefore, existing methods of construction analysis and actual construction may be severely stressed.

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.

The guideway can distort due to alignment degradation, structural creep, loss of prestress in prestressing stands, earthquake, temperature variation, or geotechnical factors. The guideway design or operating tolerances must accommodate solar-induced heat distortion.

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 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 can impact passenger comfort.

<u>Switches</u>. The guideway switch must line up two guideway sections within specified tolerances. 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 with debris or ice or snow, and vandalism. Environmental contamination, such as ice or snow build-up, could also result in switch failure.

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.

Missing and Severely Misaligned Guideway Sections. Missing and severely misaligned guideway segments could result in derailments or other catastrophes. 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. The consequences of derailment occurrences are severe, but thorough and extensive efforts will be applied during the system development phase which will substantially mitigate the risk.

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.

Earthquake. A principal hazard is a loss or misalignment 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. Large magnetic levitation gaps can reduce the risks associated with earthquakes, and has probably been an influence on the particular technologies and design gaps chosen by the Japanese.

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.

Effect of Emergency Landing Skid Use on Guideway. Use of the emergency landing skids has 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 the guideway. The sources of this hazard are design and use of emergency landing skids, especially at high speed.

"Other" Hazards

Operational maglev systems will face additional hazards beyond guideway integrity and obstruction, fouling, 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 12 noted that operator error caused one-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 10 noted that "operating practices, ineffective training, personal problems, or employee apathy" contributed to these problems. These factors highlight the need 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.

High-Speed Clamp-on and Power Grid Failure. High-speed clamp-on applies only to magnetic attractive systems. 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. 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.

Unrestrained Passengers. The instantaneous decelerations experienced during emergency braking actions and 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.

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 high rates.

Figures C-1 and C-2 in this section identify each sensor's potential for detecting a hazard. Two codes are used in each table entry The first code is a letter, H for high, M for medium, or L for low; a question mark; or a dash. This code ranks the capability of the sensor technology to effectively detect the hazard. The second code is a number, 1, 2, or 3, which indicates the maturity of the sensor technology. Code definitions are provided in Table C-1.

Table C-1 Evaluation Codes for Sensor Merit

Code	Meaning
H	The sensor technology, when "tuned" to the application, will probably meet the expected functional/performance requirements.
M	The technology has potential for this application, but may have limited effectiveness in meeting expected functional/performance requirements.
L	The sensor technology may be useful, but expected performance is low.
?	The technology is of interest, but ultimate effectiveness is unknown.
-	The technology is not suitable or appropriate for detecting this hazard.
1	High risk and technology is unproven with few, or no, existing fielded applications.
2	Medium risk and technology not fully mature or used for this application.
3	Low risk and technology is mature and currently in use for a similar application.

	Sensor									
Hazard	Microwave Radar		Millimeter Microwave Radar (MMW)		Laser Radar		Infrared Imaging		Visible Imaging	
	Wayside	Vehicle	Wayside	Vehicle	Wayside	Vehicle	Wayside	Vehicle	Wayside	Vehicle
Trespassers, suicides, maintenance personnel, large animals on guideway; Large or heavy objects thrown from above guideway	L3	L3	H2	L2	H2	M2	H2	L2	H2	L2
Impinging cars and trucks; other vehicles intentionally on guideway	M3	L3	H2	L2	H2	M2	H2	L2	H2	L2
Rockfalls, debris, limbs, train components on guideway	L3	--	M2	L1	H2	M2	H2	L2	H2	L2
Fouling by vehicle on adjacent track or guideway	--	--	--	--	--	L1	--	L1	--	L1
Train at unknown or wrong location	M3	L3	H3	L2	H3	M3	H2	M2	H2	M2
Objects hung above guideway	L3	--	M2	L2	M2	L2	M2	M2	M2	M2
Small rocks, bottles, tools, small animals, magnetic materials, etc. on guideway;	--	--	L2	L2	M2	L2	M2	M2	M2	M2
Projectiles	--	--	--	--	--	--	--	--	--	--
Dirt and mud	--	--	--	--	--	--	--	--	--	--
Snow, ice, standing water	--	--	--	--	L2	L2	M2	M2	M2	M2
Extreme hail, rain, and lightning	H3	H3	L3	L3	L2	L2	--	--	--	--
High winds, tornadoes, microbursts	H3	M3	--	--	L2	--	--	--	--	--

Figure C-1 Sensors To Detect Obstruction and Fouling Hazards

(See Table C-1 for description of sensor evaluation codes.)

Hazard	Sensor							
	Local Guideway Electromagnetic Line Sensors	Physical Line Intrusion Sensor	Canary Car	Beacons	Frangible Rods	Upward Pointed Beam	Anemometers	Acoustics for Obstruction & Fouling
Trespassers, suicides, maintenance personnel, large animals on guideway; Large or heavy objects thrown from above guideway	H2	--	H2	-- M3 (maintenance personnel only)	--	--	--	--
Impinging cars and trucks; other vehicles intentionally on guideway	H2	H3	H2	--	--	--	--	?
Rockfalls, debris, limbs, train components on guideway	M2	--	M2	--	--	--	--	?
Fouling by vehicle on adjacent track or guideway	H2	H3	L2	--	H2	M2	--	--
Train at unknown or wrong location	H2	--	M2	H3	--	--	--	?
Objects hung above guideway	M2	--	H2	--	--	--	--	--
Small rocks, bottles, tools, small animals, magnetic materials, etc. on guideway;	L2	--	M2	--	--	--	--	--
Projectiles	--	--	--	--	--	--	--	--
Dirt and mud	--	--	M1	--	--	--	--	--
Snow, ice, standing water	M2	--	H3	--	--	M2	--	--
Extreme hail, rain, and lightning	M2	--	H3	--	--	--	--	?
High winds, tornadoes, microbursts	--	--	M2	--	--	--	H3	--

C-1 Sensors To Detect Obstruction and Fouling Hazards (Concluded)

	Sensor				
Hazard	Fiber Optic	Acoustic for Guideway Integrity	Computer Vision Guideway Inspection from Vehicle	Seismic	Built-in-test Equipment
Mis-aligned Joints	H1	–	M2	–	–
Series of Mis-aligned Joints	H1	–	M2	–	–
Guideway switch failure	H1	?	–	–	H2
Switch indication failure	H1	?	–	–	H2
Earthquake	M2	?	–	M3	–
Washout	–	-	M2	–	–
Missing or severely mis-aligned guideway section	H2	?	L2	–	–
Distortion of Guideway	L1	?	M2	–	–
Separation of rails from guideway structure	–	?	M2	–	–
Guideway components mis-installed or vibrate out of place	–	–	L1	–	M1
Aging of components	–	?	–	–	M1
Effect of emergency landing skid use on guideway	–	–	M1	–	–

Figure C-2 Sensors To Detect Guideway Integrity Hazards

Hazard	Sensor Vehicle Vibration Sensor	Break Wire	Differential GPS Based Track Geometry	Guideway Geometry Car-Operational or Special Vehicle	Surveillance Camera for Guideway
Mis-aligned joints	M1	--	?	H2	--
Series of Mis-aligned joints	M1	--	?	H2	--
Guideway switch failure	--	L1	--	--	M3
Switch Indication failure	--	L1	--	--	M3
Earthquake	H2	--	--	--	--
Washout	--	--	--	M2	M2
Missing or severely mis-aligned guideway section	L3	H2	--	H3	--
Distortion of guideway	M1	--	?	H2	--
Separation of rails from guideway structure	L1	--	--	M2	--
Guideway components mis-installed or vibrate out of place	--	--	--	M2	--
Aging of components	--	--	--	--	--
Effect of emergency landing skid use on guideway	--	--	--	M2	--

Figure C-2 Sensors To Detect Guideway Integrity Hazards (Concluded)

APPENDIX D. OBSTRUCTION AND FOULING AND GUIDEWAY INTEGRITY SENSORS

Full descriptions and evaluations of all candidate sensors are provided in reference 2.

1) Look-Ahead Obstruction and Fouling Sensors

Microwave Radar

For maglev vehicle-mounted systems and for practical antenna sizes and usable detection ranges, microwave radar will not be able to discriminate cases of obstruction and fouling by vehicles on a shared right-of-way.

Microwave radar is excellent for detecting and measuring hail, rain, and in many instances, tornadoes and microbursts. It is unlikely that wayside radars dedicated to this purpose would be cost-effective for maglev use. The National Weather Service (NWS) is installing a network of advanced weather radars. If the "extreme hail, rain, and lightning" and "high winds, tornadoes, and microbursts" hazard is not mitigated by system design, then obtaining NWS radar data should be considered.

An on-vehicle radar can detect extreme hail, rain, and perhaps, lightning. Such radars are invaluable to aircraft because they can choose a new route. Maglev options are limited to slowing or stopping.

Millimeter Microwave (MMW) Radar

Wayside MMW radar is expected to be able to reliably detect large objects, including people, large animals, and vehicles. Narrow beamwidths are possible from reasonably sized antennas. As objects become smaller and closer to the guideway it is less likely that MMW radar will be able to discriminate the foreign material from the guideway under the range of environmental conditions expected.

Vehicle-mounted MMW radar will not detect obstructions at a range sufficient to allow comfortable deceleration. Some targets with a larger radar signature may be discriminable at sufficient range (6 km) to avoid collision using "urgent" deceleration rates. At 95 GHz, a 1m diameter antenna possesses a 0.18 degree beam which is 20m wide, 6 km from the vehicle. Twenty meters is 6 times the width of the guideway.

Any reflectors in this region will, to a first approximation, be indistinguishable from an obstruction on the guideway. Hazard discrimination will not be reliable with these parameters. A larger antenna size and/or the decreasing the detection range will make detection easier. Extensive study of the problem and engineering to this application could result in a usable MMW sensor.

Laser Radar

Laser radars have sufficient resolution to detect fouling, when appropriate viewing geometries are available. As noted above, rain and other weather may substantially attenuate the laser beam and shorten the maximum detection range. Laser systems are attenuated by the atmosphere and by weather and must accept high visible-light background noise.

The data rate from laser radars can be very high when their high-resolution capability is needed. For example, assume that a laser radar scans a 100m section of 3m-wide guideway, located 6 km from the vehicle carrying the sensor. Further, assume that samples are taken every 1 meter in range, and that the area scanned is a square, 5 meters by 5 meters. If samples are taken along at 0.1 meter intervals across the area scanned, then the number of samples in the volume being scanned is 100m x 1 sample/m x (5m /0.1m) x (5 m/0.1m) = 250,000 samples/volume. If the scene is resampled each time the maglev vehicle progresses by 1 meter, then at the 134 m/s top speed, there will be 33 million samples per second. One sample might be 8 bits wide, so this corresponds to approximately 250 Mbps.

Laser radars of sufficient power to detect targets at 5 to 6 km in range present a safety hazard, though use of infrared frequencies would reduce the eye hazard.

Infrared Imaging

Passive imaging sensors do not measure range. This means that objects not on the guideway may potentially be mistaken as obstructing or fouling the guideway. Researchers are examining algorithms which allow some range information to be extracted from the image.[13] It is possible that a database of unobstructed guideway images along the route could be used for comparison. Photonics and computer vision are two technologies which may be able to assist in the obstruction and fouling discrimination problem when connected to an imaging sensor. Substantial research is being conducted on image processing.

Visible Imaging

The high resolution of this type of sensor can result in very large data sets, which can drive data processing requirements and, in some architectures, communication requirements. For example, assume that the maximum resolution is available using a 0.3m diameter lens. The beamwidth will be 0.0001 degree, for a wavelength of 0.5 *u*m, and the sensor will, theoretically, be able to resolve images 0.01m apart which are located 6 km from the sensor. (6 km is the "urgent" 0.15g stopping distance of a 134m/s maglev vehicle.) Assuming that the sensor covers a 3m wide guideway and has a square image field, then 90,000 samples will be available. If a new image is obtained each time the maglev vehicle moves 1 m (7.5 ms at top speed), then there will be 134 images per second and 12 million samples per second to process. Various hardware and software strategies are available for coping with this flow as noted in the previous paragraphs.

2) Non-Look-Ahead Sensors for Obstruction and Fouling Detection

Local Guideway "Line" Sensors

An ideal obstruction and fouling sensor might be a narrow sensing "line" in space which probes the maglev operational envelope. Infrared and light beams over short distances, for example, several guideway sections (100 meters), are line sensors because their narrow beamwidths approximate a line-in-space over these short distances. Lines are narrow compared to the operational envelope and thus are not affected by false targets a short distance away. As previously discussed, beamwidth is proportional to range from the aperture and to wavelength, and inversely proportional to aperture diameter. The sensor system might use small, low-power transmitters every one to four guideway sections. Receivers would occur at the same intervals. A 1 degree beam is 1.7m wide (half the guideway width) 100m from the source. A 1 degree beam can be produced by a 0.3m diameter aperture, for wavelengths shorter than 6 mm, or frequencies greater than 50 GHz. An infrared or visible-light beam might be a few centimeters in diameter at the same distance.

Line beams could be fixed in place, used one-way (no ranging capability), used two-way (potential for ranging capability), or scanned in angle. Sandia National Laboratories examined a solid-state laser electronically scanned line system which provided range information to 100 meters.[14]

The central idea behind line sensors is to use narrow beams close to where obstruction or fouling will occur; because of the close distance, unit sensor costs may be low, and the detection and false-alarm performance high. The challenge is detecting true obstruction or fouling, while rejecting false targets, and doing this at low cost. The low cost is important because this method of instrumenting the operational envelope would use many sensors. Likewise, the large number of sensors present means that the false-alarm rate for individual sensors must be held very low if the entire system is to have an acceptably low sensor false-alarm rate.

Microwave and MMW sensors, when installed to cover one or a few guideway segments, will certainly be able to reliably discriminate impinging cars and trucks, etc., and maglev vehicles. Smaller obstructions, such as people, branches, and other objects of this size are reliably detectable, particularly at the MMW, or higher microwave frequencies. Snow, ice, and standing water are probably discriminable if the sensors are engineered for that purpose. Objects suspended above the guideway may be missed if the systems are "tuned" to detect obstruction and fouling close to the guideway.

Physical Line Intrusion Sensor

Physical line sensors are cables normally deployed adjacent to a fence protecting the maglev on a shared right-of-way. The cables alarm if the right-of-way is violated by an impinging vehicle. Because of their placement, they can be expected to reliably detect vehicles impinging from an adjacent highway or railway.

Canary Car

The canary car would carry obstruction, fouling, and guideway integrity sensors 10 or more kilometers ahead of revenue-service maglev vehicles. This concept would employ some of the sensors considered for a revenue-service vehicle. It would be very light and able to stop quickly. Because of the rapid stopping capability, it need not sense as far ahead as a full-size maglev vehicle to detect and avoid obstruction or fouling. The concept has high or medium potential for detecting all obstruction or fouling hazards except projectiles and fouling by vehicles on an adjacent right-of-way. The projectile hazard is short -lived; therefore, detection by a canary car is not useful.

Fouling by an adjacent vehicle could be detected in some circumstances, but protrusions from the adjacent vehicle may be difficult for the canary car to detect. Further, if the adjacent vehicle is approaching the maglev vehicle, then to prevent damage, both vehicles must be alerted and stopped, in much less than the usually allotted time.

The canary car could detect small objects and remove them from the guideway.

Beacon

Beacons can be effective for detecting trains at unknown or wrong locations. They can be effective for warning of maintenance personnel and construction sites. For maintenance personnel to be detected, they must wear the beacons, or have them nearby. In either case, beacon batteries must be charged and the beacon turned on. For these reasons, the effectiveness in protecting maintenance personnel is marginal. The maglev control system would be cognizant of work sites and all vehicle locations. If unexpected beacon returns were detected, the control system would be alerted and the vehicle stopped.

Frangible Rods

Frangible (easily broken) rods might be used to detect a fouling vehicle. If placed to encompass the maglev operational envelope, then these sensors could be highly effective in detecting fouling. The technology does not appear to be difficult, but since it has not been used for this purpose there is medium technology risk.

Upward-Pointed Beam

Upward-pointing electromagnetic beams may be suitable for detecting some obstruction and fouling hazards. Suitably placed, they could detect fouling by vehicles on shared right-of-ways. They also may be able to measure snow and ice accumulation at specific points.

Anemometers

Suitably placed anemometers can measure and detect high winds due to any source. The technology is mature. A drawback is that some sources of very high winds, tornadoes and microbursts, for example, are small and can easily slip through an anemometer net. The sensor net could be made denser to detect these hazards, but given their rarity and short lifes, it is not clear that this would be cost beneficial.

Acoustics for Obstruction and Fouling

Acoustic refers to measurement of vibration energy created by hazards and transmitted through the guideway structure. This technology may be usable (in an active implementation) to detect the presence of a maglev vehicle. Impinging highway vehicles might be detected by the acoustic impact energy transmitted through the structure.

Sensors for Guideway Physical Integrity Detection

This section considers sensors to determine alignment tolerance and overall guideway integrity.

Table D-1 shows installation accuracy values for the Transrapid system.[15] Transrapid is a magnetic-attractive system. A magnetic-repulsive system will not require such stringent guideway tolerances. The reference states that the Stage 4 values should be taken as limiting values relative to adjacent beams. Absolute positioning accuracy values are applied during construction, to ensure that the installation is adequately close to a precalculated space curve. The Stage 3 values shown are for Transrapid installation purposes, and undoubtedly reflect the available beam adjuster capability. Here they are taken as a first estimate of maximum absolute position deviations which might be allowable in service. Ideally, adjacent beam positions would be measured with sufficient (relative, absolute) accuracy so that long-term trends may be measured and any problems noted early. If that is not found to be desirable, perhaps due to cost or technical limitations, then at a minimum, an out-of-tolerance threshold must be established and maintained.

Transrapid used laser-based surveyor's equipment to perform initial alignment. Surveyor's equipment would not be suitable for in-place alignment monitoring; however, the principle is sound and may be viable as an installed-in-place means for measuring guideway section-to-section displacements, shifts, or values. The laser path would be enclosed to prevent environmental effects from degrading the measurements.

Table D-1 Transrapid Installation Alignment Tolerances

Stage 4 - Fine positioning of the beams (Accuracies are limits relative to adjacent beams)	x-direction: ± 2 mm y-direction ± 1 mm z-direction ± 1 mm
Stage 3 - Beam support alignment (Reference is ambiguous, but this appears to be an absolute accuracy relative to calculated space curve)	± 5 mm

Fiber Optics

Fiber-optic sensor systems possess attractive characteristics, including the elimination of many active components, compactness, potential for low cost, immunity to interference, and low signal attenuation. Fiber optics have received significant attention for telecommunications purposes. The military has been a significant advocate for these sensor technologies.

Fiber-optics technology is attractive because of its potential to perform multiple transducing functions which may be required for monitoring guideway integrity. It is possible, for example, that one fiber-optic line feeding a guideway could probe five locations and measure three parameters in each location, with no active components located on the guideway.

Of course, fiber optics are only one means to implement the sensing functions described below. A variety of other technologies are possible and should be considered should a requirement to measure the corresponding guideway characteristics be confirmed.

Pressure

Pressure sensing may be useful for detecting inter-section guideway alignment errors resulting from misaligned joints or a series of misaligned joints. Fiber-optic line would be laid along the length of the guideway; restraints between guideway sections would transmit inter-section guideway motion to the fiber. A fiber light source/receiver/processor would drive sensors on many guideway sections. Fiber-optic pressure sensors have high technical potential for this role. The technical risk is high, since no such sensors have been used in this application, and many sensors would be required over long distances in an unprotected environment.

Vibration

Fiber-optic vibration sensors might be used as the transducers for the acoustic or vibration sensors described in other paragraphs.

Alignment

Alignment sensors would measure the relative alignment between two guideway sections. Trends could be monitored and alignment differences exceeding thresholds could be used to trigger further inspection or alarms.

Alternatively, gross alignment characteristics might be detected by checking for the light transmitted through the co-location of two fiber-optic line ends. This could be particularly useful for detecting guideway switch failures and guideway switch indication failures. For that application, two fiber ends would coincide in the event of proper switch alignment. Modulated light could be sent down one fiber, or set of fibers, and a receiver at the end of a second fiber could detect the presence or absence of that modulation, and report the results to the maglev control system.

Acoustics for Guideway Integrity

Acoustics, or sound waves, may be used to measure some guideway characteristics. Signals may be injected into the guideway structure and the response measured, or the guideway response to normal events, such as maglev vehicle passage, may be monitored.

Computer Vision Guideway Inspection from Vehicle

Computer vision techniques may also be usable for automated guideway inspection using computers attached to electronic cameras and, perhaps, other sensors. Computer vision and processing has been used for examining conventional rail. Reference 17 describes a computer vision system called optical rail wear inspection and analysis system (ORION), that Canadian National began testing in 1986. Reference 18 describes a different system which also relies on electronic cameras to examine rail dimension. The ORION system "was the first time a machine vision system was used for rail image recognition and reporting in real time". The experience on that system indicated, as expected, that extensive field validation is necessary to properly develop and "tune" the processing algorithms. Guideway inspection requirements will be more stringent than for existing rail and so will push this technology's capabilities.

Computer vision has potential for detecting guideway misalignments and distortion but, because of the potentially stringent guideway alignment requirements, operational effectiveness must be demonstrated. The technology has potential for detecting separation of rails from the guideway structure, monitoring the effect of emergency landing skid use, and for detection of some guideway components which are mis-installed or vibrate out of place. The latter may require special camera positioning distinct from positioning required for other applications. This technology may be used to detect missing or severely misaligned guideway sections, but lack of timely detection limits usefulness.

There is a medium technology risk for these applications. The technology is emerging, and not fully mature for these applications.

Seismic Sensors

Seismic sensors would be used to detect earthquakes in progress, with the intent of slowing or stopping all vehicles safely until the quake-in-progress settled and until the integrity of guideway, control, propulsion, passenger facilities, etc. have been re-established. The technology is mature but may have limited effectiveness since detection of a quake in progress does not ensure that vehicles can be stopped in time to avoid damage.

Built-in-test Equipment

Built-in-test equipment (BITE) has potential for detecting guideway switch failure and switch indication failure. Careful design and extensive testing will be required to ensure that guideway switch monitoring BITE possesses the required high availability, reliability, and integrity. BITE may have applicability to detection of some mis-installed guideway components, or guideway components which vibrate out-of-place. For example, BITE sensors could be installed to detect guideway component motion or to monitor key component characteristics during the life of the system.

BITE has applicability throughout the maglev system.

On-vehicle Vibration Sensing

Guideway section-to-section alignment errors and guideway distortions may be detectable through use of on-vehicle low frequency vibration sensors. Relative beam lateral displacements of perhaps a few millimeters will have to be detected at the inter-beam boundaries to detect small inter-section lateral or vertical displacement errors. Inter-section lateral displacements may be easier to detect than angular misalignment or guideway distortion, because the inter-section lateral displacement occurs over a small distance at the interface between two sections.

Guideway distortions may be detectable in the same manner. This method will easily detect and record the location of severely misaligned beams. It has no operational value for missing guideway section detection. It is possible that this method will be able to detect the separation of rails from the guideway structure, depending on the system design selected and on the resulting characteristics of separated rails.

Break Wire

This technology is based on wire or optical fiber channeled through the guideway and designed to break, or drastically change electrical or optical characteristics upon "significant" inter-section guideway movement. This technology has high potential for this purpose, but represents a medium technology risk.

Differential GPS Positioning for Geometry Measurement

Researchers have been investigating highly accurate differential applications for the new Department of Defense global positioning system (GPS). This technology has potential for positioning guideway geometry car sensors to within centimeters for precise annotation. This will facilitate detailed examination of anomalous and unusual measurements and will support trend analysis. Depending on the required maglev system guideway positioning accuracies, and on the ultimate differential positioning accuracy of GPS, this technique may be useful for detecting gross guideway movements, including absolute shifts and trends. This positioning technique would be independent of any precision positioning provided as part of the maglev propulsion system and would allow simultaneous inspection of that positioning system. Differential GPS is being examined for use on conventional-rail geometry cars.[19,20] Current implementation accuracy requirements are not as demanding as will be required for maglev.

Guideway Geometry Inspection Car

A special vehicle, or a revenue service vehicle, would be equipped with guideway inspection equipment. The car has medium or high potential for measuring many guideway characteristics, but the required technology is not fully mature.

The sensor evaluation table notes that the inspection car has high potential for detecting missing or severely misaligned guideway sections. This capability would not be used under ordinary circumstances, but might be used following an earthquake, for example, to rapidly confirm system integrity.

Surveillance Cameras for Guideway

Surveillance cameras, using visible or infrared light, might be used to monitor guideway switches and areas where washouts or similar hazards are a special concern. The camera image could be monitored by computer for changes, or fed directly to an operator to confirm normal operating conditions.