U.S. Department
of Transportation
**Federal Railroad
Administration**

Noise from High Speed Maglev Systems

National Maglev Initiative
Washington, D.C. 20590

Noise Sources

Noise Criteria

Preliminary Design Guidelines for Noise Control

Recommendations for Acoustical Test Facility for Maglev Research

DOT/FRA/NMI-92/18

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[1] OASIS, 5 Militia Drive, Lexington, MA 02173

[2] Consultant, 9 Cliff Street, Marblehead, MA 01945

16. Abstract

Noise levels from magnetically-levitated trains (maglev) at very high speed may be high enough to cause environmental noise impact in residential areas. Aeroacoustic sources dominate the sound at high speeds and guideway vibrations generate noticeable sound at low speed. In addition to high noise levels, the startle effect as a result of sudden onset of sound from a rapidly moving nearby maglev vehicle may lead to increased annoyance to neighbors of a maglev system. This report provides a base for determining the noise consequences and potential mitigation for a high speed maglev system in populated areas of the United States. Four areas are included in the study:

(1) definition of noise sources;

(2) development of noise criteria;

(3) development of design guidelines; and

(4) recommendations for a noise testing facility

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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)

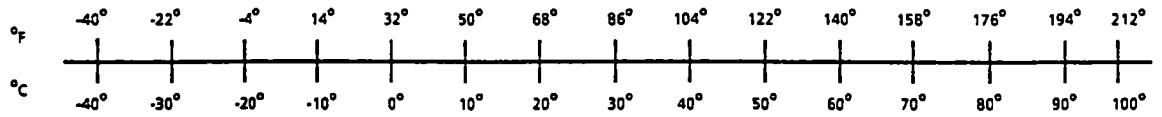
1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

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.

SECTION 1

NOISE SOURCES OF HIGH SPEED MAGLEV TRAINS

TABLE OF CONTENTS

LIST OF FIGURES

PREFACE

This report is the first of four reports to be prepared under U.S. Department of Transportation Contract # DTFR53-91-C-00074, "Noise from High Speed Magnetically Levitated Transportation Systems." The reports under this contract cover the following areas:

1. Characterization of Noise Sources
2. Noise Criteria for High Speed Maglev Systems
3. Preliminary Design Guidelines based on Noise Considerations
4. Recommendations for Acoustic Test Facility for Maglev Research.

It presents information on the noise data obtained from the German testing programs on the TransRapid system, describes sources of noise from maglev systems, quantifies the potential environmental noise impact from hypothetical systems installed in the United States, and identifies further research needs for resolving the unknowns related to sound sources on high speed surface transportation vehicles. The focus of this report is the noise from the TransRapid maglev system because it is likely to be the first such system in operation in the United States. Information from the extensive Japanese effort in maglev research may be included in a future report as it becomes available.

EXECUTIVE SUMMARY

Noise is a major concern when any new transportation source is introduced into the existing surface transportation network. Maglev will be no exception. Despite the perception that there will be no problem in comparison with other noisy sources, such as diesel-hauled passenger and freight trains, it is worth investigating the potential of a noise problem early enough in the process that mitigation, if necessary, can be implemented during the design.

I. Environmental Noise Impact

Scenarios with high speed (400 Km/hr or 111 m/sec) maglev traffic based on the schedule of the Northeast Corridor show that without implementation of mitigation measures, noise levels from a high speed maglev system could be great enough to evoke negative public reaction. The evidence is as follows:

1. Maximum noise levels from high speed passbys of a vehicle like the current generation TransRapid 07 are in excess of those which are known to cause negative public reaction.

2. Long term noise exposure from regularly scheduled high speed maglev passenger service could cause impact in heavily traveled high speed corridors in residential areas according to newly proposed noise criteria.

Consequently, special consideration should be given to testing and incorporating noise control techniques at the design stage of any system that is adopted.

II. Noise Characteristics of Maglev

Key descriptors of noise from a maglev system are the maximum noise level of a passby, the distribution of sound energy in a frequency spectrum and the total sound energy of a passby.

Maximum level (Lmax) at a reference distance of 25 m from a maglev depends strongly on speed. The speed dependency is approximately 30 times the logarithm to the base ten of speed (expressed as 30 log(speed)) for speeds below 250 Km/hr (69 m/sec), and 60 log (speed) above 250 Km/hr (69 m/sec). Lmax from maglev on elevated guideway is typically 5 dBA lower than conventional high speed trains at-grade at the same speed.

Frequency spectrum of the TR 07 maglev compared to conventional high speed trains indicates that maglev is quieter in the high frequencies (above 1250 Hz) and in the low frequencies (below 160 Hz), but has the same level in the mid-frequency range (160 Hz to 1250 Hz).

Sound Exposure Level (SEL), the basic unit for calculating environmental noise impact, shows that the TR 07 maglev on elevated guideway and conventional high speed trains at-grade (French TGV and German ICE) emit essentially the same sound energies per unit length in the speed range of 165 Km/hr (46 m/sec) to 400 Km/hr (111 m/sec). This very important result suggests that the environmental noise effects of the current generation maglev are the same as those from conventional high speed rail systems.

III. Noise Sources

Noise from a high speed rail system is generally dominated by three sources: the propulsion and auxiliary equipment, mechanical/structural radiation and airflow moving past the train. The sources differ in where they occur in the system and in what frequency range they dominate. An overview of noise sources occurring on maglev trains is as follows:

Propulsion Noise Sources. Noise from the magnets in a maglev system is a result of induced vibration from magnetic forces. One source of vibration is oscillating magnetostriction, which is likely to be tonal in character. Another effect of magnetic traction is sound at the pole passing frequency; the interaction of the moving vehicle and the stationary magnetic poles at a uniform spacing causes a tonal sound which varies as the velocity. Location of these forces is at the magnet gaps between the vehicle and the guideway, and radiation can come from there as well as from larger structures (vehicle panels, guideway, etc.) caused to vibrate in response to such forces.

Mechanical/structural Noise Sources. Maglev technology is not free from mechanical/structural sources despite the contactless nature of the system. The maglev support system noise sources are:

1. wheels rolling on guideway support surfaces at low speeds for electrodynamic levitated systems (this type of maglev requires forward motion before lift can occur), and

2. magnetic pole passing (variation in force as magnetic poles pass over each other).

The maglev guideway structure is subject to loading forces as the vehicle moves over the guideway, causing vibrations and radiated sound from the guideway. The vehicle body construction may also respond to dynamic forces, resulting in vibration and sound radiation.

Aeroacoustic Noise Sources. Aeroacoustic sources dominate the noise emission from high speed maglev vehicles. Noise from airflow over a train is generated by flow separation and reattachment at the front, turbulent boundary layer over the entire surface of the train,

flow interactions with edges and appendages, and flow interactions between moving and stationary components of the system. Airflow-generated, or aeroacoustic, sources result in increases in noise ranging from 50 to 80 times the logarithm of train speed and generally dominate noise levels from high speed trains at speeds of 250 Km/hr (69 m/sec) or greater, depending on the significance of the mechanical/structural noise. Aeroacoustic sources generally radiate sound in the frequency range of 250 Hz to 500 Hz. These sources can be located over the entire surface of the train and at the edges of guideway structure.

IV. Future Noise Research Program

The conclusions of this report suggest a strategy for future research related to noise from a maglev system. Mechanical/structural noise tests are best performed on full scale facilities, but there are two approaches to research for aeroacoustic problems; model testing in wind tunnels, or full scale (possibly quarter or half scale) on a test track. The choice revolves around the extent to which structural re-radiation is found to be important.

The model testing may be worth doing anyway, because aerodynamic drag measurements will most likely be done in scale model wind tunnel testing. Model testing can give scale measurement of the direct radiation component and will provide an easier method for sorting out the various aeroacoustic mechanisms. On the other hand, if structural radiation is found to be important, then testing will be required on a full-, or nearly full-scale prototype. Two approaches are as follows:

1. Build a full scale maglev test facility in the U.S., along with a complete acoustical testing capability, or,

2. Gain access to a full scale test facility in another country.

The former would require a major U.S. commitment to maglev development, while the latter would involve a collaboration with Germany or Japan. A joint effort with one of the existing test programs would likely result in a more expedient resolution of the noise issues.

1. INTRODUCTION

Noise from high speed magnetically levitated trains (maglev) has not been considered a potential environmental problem. The commonly held perception is that if the vehicle is suspended above a rigid guideway, then the only noise is the sound of the wind. One reference calls maglev "inherently quieter than existing rail systems."[1] In contrast with noisy freight trains or rumbling subway trains, the public believes they should welcome a maglev into their community. However, analysis of available data from maglev development programs reveals that, although maglev holds promise for quiet operation, the noise levels from very high speed maglev may be great enough to cause environmental impact in residential areas. Introduction of a new transportation system, like maglev, into the existing environment may be more difficult than expected for its very high speed operations. Consequently, mitigation of adverse noise effects must be taken into consideration at the outset, preferably during the development of maglev. Research on this exciting mode is still in its early stages and just as in its other developmental areas the noise control effort will move forward during the design and development process. If incorporated early in the process, noise control solutions will be found for the noise problems.

This report needs to present maglev noise information in a way that is technically accurate, but at the same time understandable outside the acoustical profession. The text often uses specialized acoustical terminology which may be unfamiliar to many readers. The basic terms and noise descriptors are introduced in the following sub-section.

1.1 Basic Acoustical Terminology

The sounds that we hear are the result of very small pressure fluctuations in the atmosphere around us. In order to describe the signal content of these pressure fluctuations, acousticians have developed methods of analysis that differentiate among loudness, pitch and time history of sound. This sub-section is intended as a brief introduction to the descriptors to be used in this report. More detail can be found in an acoustical text or noise control handbook. Although some authors take care to define them separately, throughout this report we use the terms "sound" and "noise" interchangeably.

1.1.1 Noise Level, Decibels

Sound is a description of pressure oscillations above and below the mean atmospheric pressure. The amplitude of oscillation is related to the energy carried in a sound wave; the greater the amplitude, the greater the energy, and the louder the sound. The mean value of the pressure oscillations is always the atmospheric pressure; consequently, to describe an effective value of sound pressure, we use the root mean square pressure. The full range of sound pressures encountered in the world is so great that it becomes more convenient to compress the range by the use of the logarithmic scale, resulting in one of the fundamental descriptors in acoustics, the **sound pressure level, (L_p)**, defined as:

$$L_p = 20 \log_{10} (p/p_{ref}), \text{ in decibels (dB), where}$$

p is the sound pressure and p_{ref} is the reference sound pressure, internationally adopted to be 20 micropascals. In this report, the term **noise level** also refers to the sound pressure level, L_p.

1.1.2 Frequency Spectrum, A-Weighting

In Section 1.1.1 we relate noise level to the amplitude of pressure oscillations. Another aspect of the oscillation is its **frequency**, the number of complete cycles above and below the mean value that occurs in a unit time. The unit is cycles per second, called Hertz (Hz). When a sound is analyzed, its energy content at individual frequencies is displayed over the range of frequencies of interest, usually the range of human audibility from 20 Hz to 20,000 Hz. This display is called a **frequency spectrum**. Three types of spectra are commonly used in acoustics: narrow band, where the sound energy is divided into equal frequency units of constant bandwidth, e.g. one Hertz or five Hertz bands; octave band, and one-third octave band, where the sound energy is

divided among constant percentage bandwidths of 70% and 23% of the center frequency, respectively. This report uses one-third octave band spectra as a diagnostic tool for differentiating among sound sources because they are narrow enough to provide detailed information about the frequency content of a wideband noise signal, yet not too narrow to be sensitive to frequency shifts by Doppler effects of moving sources.

Sound is measured using a sound level meter, with a microphone that is designed to respond accurately to all audible frequencies. On the other hand, the human hearing system does not respond equally to all frequencies. Low frequency sounds below about 400 Hz are progressively and severely attenuated, as are high frequencies above 10,000 Hz. To approximate the way the human interprets sounds, a filter circuit with the same frequency characteristics as the typical human hearing mechanism is built into sound level meters. Measurements with this filter enacted are referred to as **A - Weighted Sound Pressure Levels**, expressed in **dBA**. Sounds at frequencies below 20 Hz (infrasound) and above 20,000 Hz (ultrasound) are generally imperceptible by the human hearing system and are consequently neglected in an acoustical analysis.

1.1.3 Noise Descriptors: Lmax, Leq, SEL and Ldn

Another characteristic of sound in the environment is its fluctuation in level over time. Several descriptors have been developed to provide single number metrics for these variations. The time history of a typical maglev passby is shown in Figure 1. As the vehicle approaches, passes by, and recedes into the distance, the sound pressure levels rise and fall accordingly. Although detectable at levels slightly lower than the background sound level, the passby event is considered to occur over a duration containing most of the sound energy, such as within 10 dBA or 20 dBA of the peak. Note that although it looks like a great deal of the passby sound energy lies below the background level, the vertical scale is actually a logarithmic quantity, so each 10 dB increase represents 10 times the sound energy.

The descriptor used for representing the highest sound level of a single event, such as the passby of a maglev vehicle in Figure 1, is the **Maximum Level, Lmax**. Lmax in dBA is commonly used to compare noise levels from different vehicle passbys, but it is important to understand that unless the sound is steady and continuous, the maximum level occurs for only a short time during an event. It is usually dominated by the single loudest source, which may be only one vehicle in a long train. Lmax associated with commonly experienced noise events is shown in Figure 2. A shortcoming of Lmax is that it ignores the duration of the event, an important environmental consideration. A single event descriptor that accounts for both level and duration of a sound

is the **Sound Exposure Level, SEL,** which is a single number unit in decibels that describes all the sound energy received at a given point from an event like that depicted in Figure 1, but normalized to a one-second duration. Technically, the duration of the entire event must be

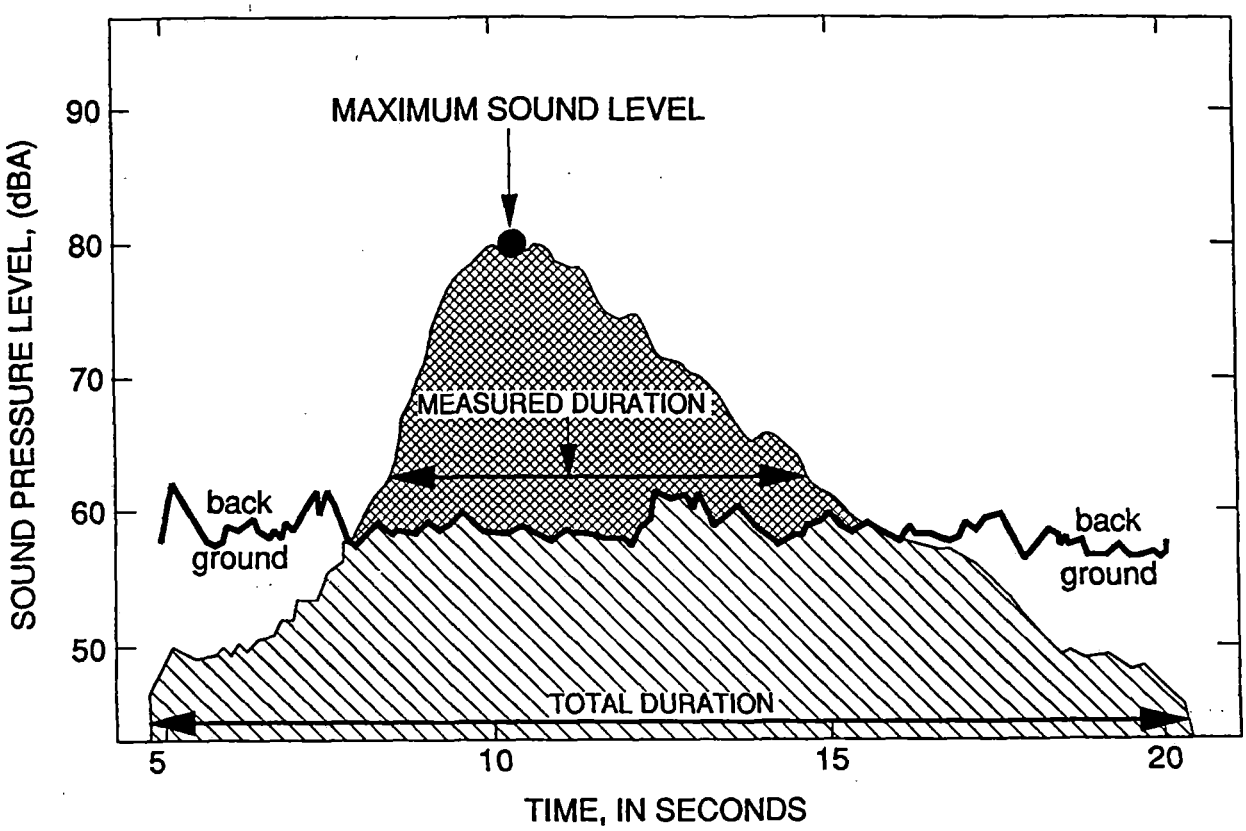


Figure 1. Typical Noise Time History of a Vehicle Passby

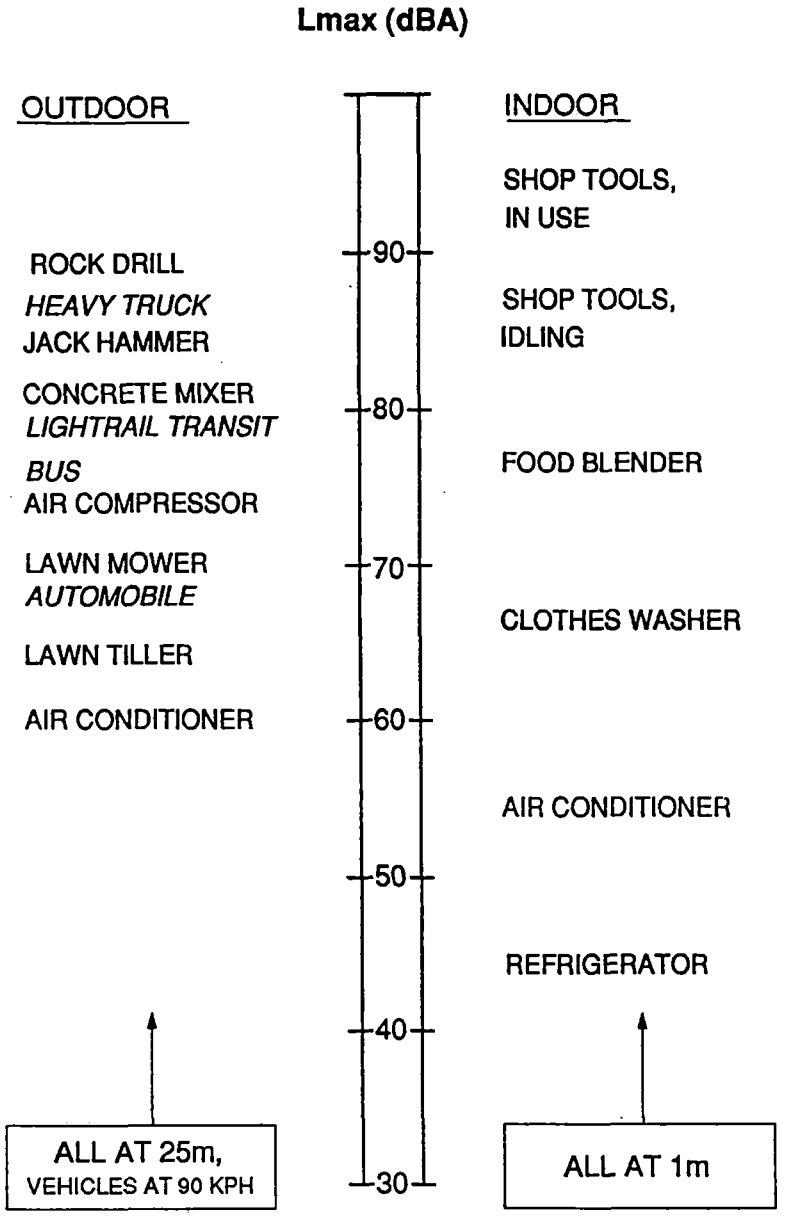


Figure 2. Commonly Experienced Noise Levels

included in the normalization; however, in practice a duration like that shown in Figure 1 as "measured duration" is used because it is difficult to measure noise from portions of events below the background level. The normalization to one second allows comparison of the sound energy, and eventual combination, of different types of events on a common basis. For example, the SEL can be used to compare the sound energies emitted by various kinds of trains, even if they have different lengths.

The descriptor used for cumulative noise exposure in the environment is the **Equivalent Sound Level, Leq.** This is the level of a steady sound which, over a referenced duration and location, has the same A-weighted sound energy as the fluctuating sound. The duration of one hour is commonly used in environmental assessments. Researchers in Germany often describe train noise by the "passby level" which is the Leq over the time it takes for the train to pass. The "passby level" is typically somewhat lower than the actual Lmax because it is less influenced by a single dominant source. Environmental impact assessments in the United States use the **Day-Night Sound Level, Ldn.** Ldn is a 24-hour Leq, but with a 10 dB penalty assessed to noise events occurring at night during the hours of 10 pm to 7 am. Ldn has been found to correlate well with the results of attitudinal surveys of residential noise from transportation sources. It is the designated metric of choice of many Federal agencies, including Department of Housing and Urban Development (HUD), Federal Aviation Administration (FAA), Urban Mass Transportation Administration (UMTA) and Environmental Protection Agency (EPA).

2. NOISE OF MAGLEV COMPARED WITH OTHER HIGH SPEED TRAINS

Noise is a major concern when any new transportation source is introduced into the existing surface transportation network. Maglev will be no exception. Despite the perception that there will be no problem in comparison with other noisy sources, such as diesel-hauled passenger and freight trains, it is worth investigating the potential of a noise problem early enough in the process that mitigation, if necessary, can be implemented during the design process.

Maglev is likely to be compared with other high speed transportation modes in future studies of corridor alternatives. High speed rail systems are now in operation in several countries and their noise characteristics have become familiar. By comparing the noise characteristics of maglev with those of conventional high speed rail systems, we gain perspective on how the noise from a maglev system may be received by communities.

2.1 Overview of Noise Sources

Maglev and conventional high speed train noise sources have many similarities. Noise from a high speed rail system is generally dominated by three sources: the propulsion and auxiliary equipment, mechanical/structural radiation and airflow moving past the train. The sources differ in where they occur on the system (Figure 3a, 3b and 3c) and in what frequency range they dominate. This section provides an overview of noise sources occurring on both conventional and maglev trains. Each source is discussed in more detail in Section 4.

2.1.1 Propulsion noise sources

High speed trains are electrically powered; the propulsion noise sources are those from electric traction motors or electromagnets, control units and associated cooling fans. Fans have been found to be a major source. On conventional trains, major cooling fans are located near the top of the power cars, about 3.5 m above the rails, as indicated in Figure 3c; they dominate the noise spectrum in the frequency bands near 1000 Hz. External cooling fan noise tends to be constant with respect to train speed, although some traction motors have internal cooling fans which rotate at the same speed as the motors.

Noise from the magnets in a maglev system is a result of induced vibration from magnetic forces. One source of vibration is oscillating magnetostriction, which is likely to be tonal in character. Another effect of magnetic traction is sound at the pole passing frequency; the interaction of the moving vehicle and the stationary magnetic poles at a uniform spacing causes a tonal sound which varies as the velocity. These forces are located at the magnet gaps between the vehicle and the guideway, and radiation can come from there as well as from larger structures (vehicle panels, guideway, etc.) caused to vibrate in response to such forces.

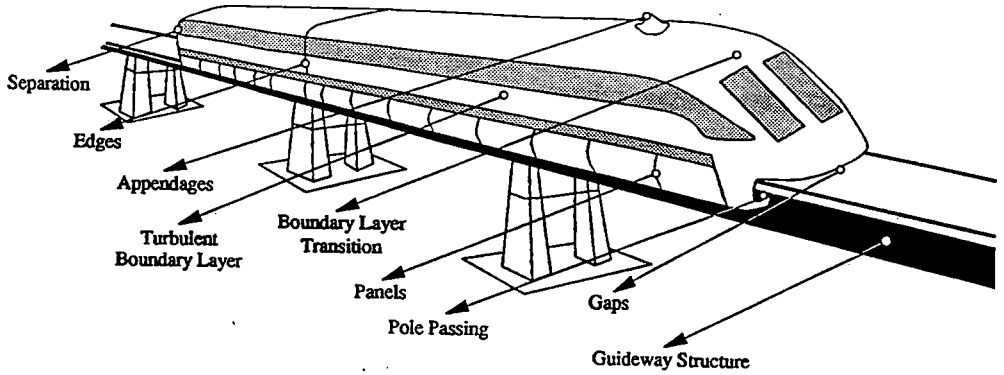


Figure 3a. Noise Sources on an Electromagnetic Maglev System

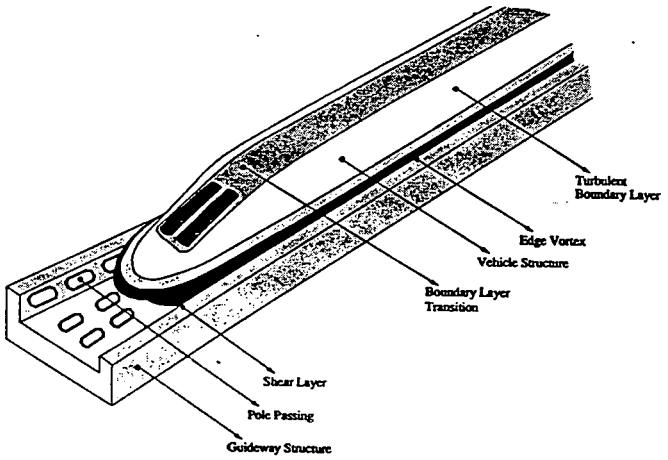


Figure 3b. Noise Sources on an Electrodynamic Maglev System

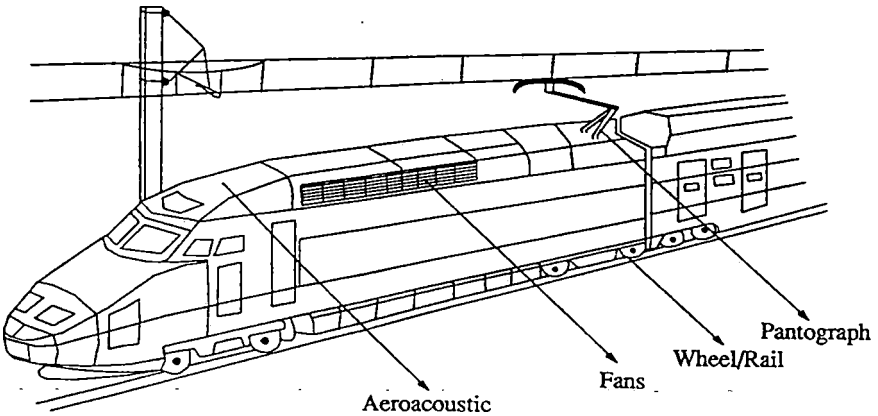


Figure 3c. Noise Sources on a Conventional High Speed Train

2.1.2 Mechanical/structural noise sources

The effects of wheel/rail interaction on conventional trains, guideway structural vibrations, and vehicle body vibrations fall into the category of mechanical noise sources. Wheel/rail interaction is the rolling noise radiated by steel wheels and rails caused by small roughness elements in the running surfaces. This noise source is close to the trackbed with an effective height of about 0.8 m above the rails (Figure 3c). It generally shows up in the noise spectrum in the 2000 Hz to 4000 Hz frequency range and often dominates the A-weighted sound level of conventional trains. However, wheel/rail noise can be effectively shielded by low barriers. Wheel/rail noise increases at a rate of approximately 30 times the logarithm of train speed (expressed as 30 log (speed)). Extensive noise measurements taken by the French National Railroad (SNCF) over a wide range of speeds show that wheel/rail noise dominates the A-weighted sound level from TGV trains at speeds up to 300 Km/hr (83 m/sec). The German Railroad found that the new ICE trains with damping devices on the wheels are dominated by wheel/rail noise up to about 250 Km/hr (69 m/sec).

Other mechanical noise sources are the guideway vibrations and vehicle body vibrations. Both of these sources tend to radiate sounds at very low acoustical frequencies: fundamental resonance frequencies of guideway support beams are generally below 10 Hz, with radiation from box beam panels up to about 80 Hz. Vehicle body vibrations depend on the details of skin and body panel construction, but they can result in significant sound radiation throughout the audible range.

Maglev technology is not free from mechanical/structural sources despite the contactless nature of the system. The maglev analogies to wheel/rail noise from a conventional train are:

1. noise from wheels rolling on guideway support surfaces at low speeds for electrodynamic levitated systems (this type of maglev requires forward motion before lift can occur), and

2. noise from magnetic pole passing (discussed in Section 4.2).

Moreover, maglev guideway structure is subject to similar loading forces as a conventional train, leading to similar vibrations and radiated sound from the guideway. The vehicle body constructions may also be similar to conventional train cars in response to dynamic forces, resulting in similar vibration and sound radiation characteristics.

2.1.3 Aeroacoustic noise sources

Noise from airflow over a train is generated by flow separation and reattachment at the front, turbulent boundary layer over the entire surface of the train, flow interactions with edges and appendages, and flow interactions between moving and stationary components of the system. Aeroacoustic sources result in increases in noise with speed ranging from 50 to 80 times the logarithm of train speed and generally dominate noise levels from high speed trains at speeds of 250 Km/hr (69 m/sec) or greater, depending on the significance of the mechanical/structural noise. Aeroacoustic sources generally radiate sound in the frequency range of 250 Hz to 500 Hz. These sources can be located over the entire surface of the train and at the edges of guideway structure.

2.2 Maximum Noise Level (Lmax)

Maglev has the potential of being quieter than other modes of transportation - especially at speeds below 100 Km/hr (28 m/sec). At very high speeds, maglev's advantage is diminished. Plotted in Figure 4 are maximum noise levels in dBA of several electrically powered high speed rail systems on guideways with which they are most often associated. The data are from the following systems:

- TR 07 refers to the current generation electromagnetic levitated vehicle undergoing tests at the Emsland Test Track in Germany; the length of a two- car train is 50m. The guideway is elevated. Noise data were reported by TUV Rheinland[2].

- ICE refers to the German National Railroad high speed passenger train, the InterCity Express (ICE); measured data were taken on a train consist of 2 power cars and 3 coaches, with a total length of 120 m. Track is ballast and tie at-grade. Noise data were reported by TUV Rheinland (ref. 2).

- TGV refers to the French National Railroad high speed passenger train, the Tres Grande Vitesse (TGV); measured data were taken on a train consist of 2 power cars, 2 transition cars and 8 coaches, with a total length of 237.5 m. Track is ballast and tie at-grade. Noise data were reported by TUV Rheinland (ref. 2).

- AMTRAK refers to a test train with a Swedish electric locomotive (AEM-7) during demonstrations on the U.S. Northeast Corridor; measured data were taken on a

consist of locomotive and 5 coaches with a total length of 115 m. Track is ballast and tie at-grade. [3]

- Shinkansen refers to the Japanese "Bullet Train"; Shinkansen data are from Japanese National Railways, length is probably 16 cars[4].

Figure 4 illustrates three important issues relevant to quantifying the potential maglev noise impact:

1. A passby of the TR 07 maglev two-car train on elevated guideway is about 5 dB quieter than the 5-and 12-car European high speed trains at-grade for comparable speeds.

2. Noise levels for <u>all</u> trains are significant at speeds above 200 Km/hr (56 m/sec), approaching or exceeding 100 dB at the reference distance for the highest speeds shown in the graph.

3. Similar noise vs. speed behavior appears for electric high speed rail vehicles, whether maglev or wheeled. Mechanical noise (wheel/rail noise, structural radiation, etc.) at low speeds tends to have a low order speed dependency, like 30 times the logarithm of speed, whereas aeroacoustic noise at high speeds has a strong speed dependency, like 60 to 80 times the logarithm of speed. The transition between the two speed regimes occurs in the range of 250 to 300 Km/hr (69 to 83 m/sec), depending on the magnitude of the wheel/rail or mechanical noise.

It may be surprising to some that maglev noise data shows a mechanical/structural type of speed dependency at speeds below 250 Km/hr (69 m/sec). It is shown in Section 4.3 that the contribution to wayside noise from the maglev vehicle interaction with the guideway is very much in evidence at lower speeds. At high speeds, aeroacoustic sources dominate the noise from all of these electric trains.

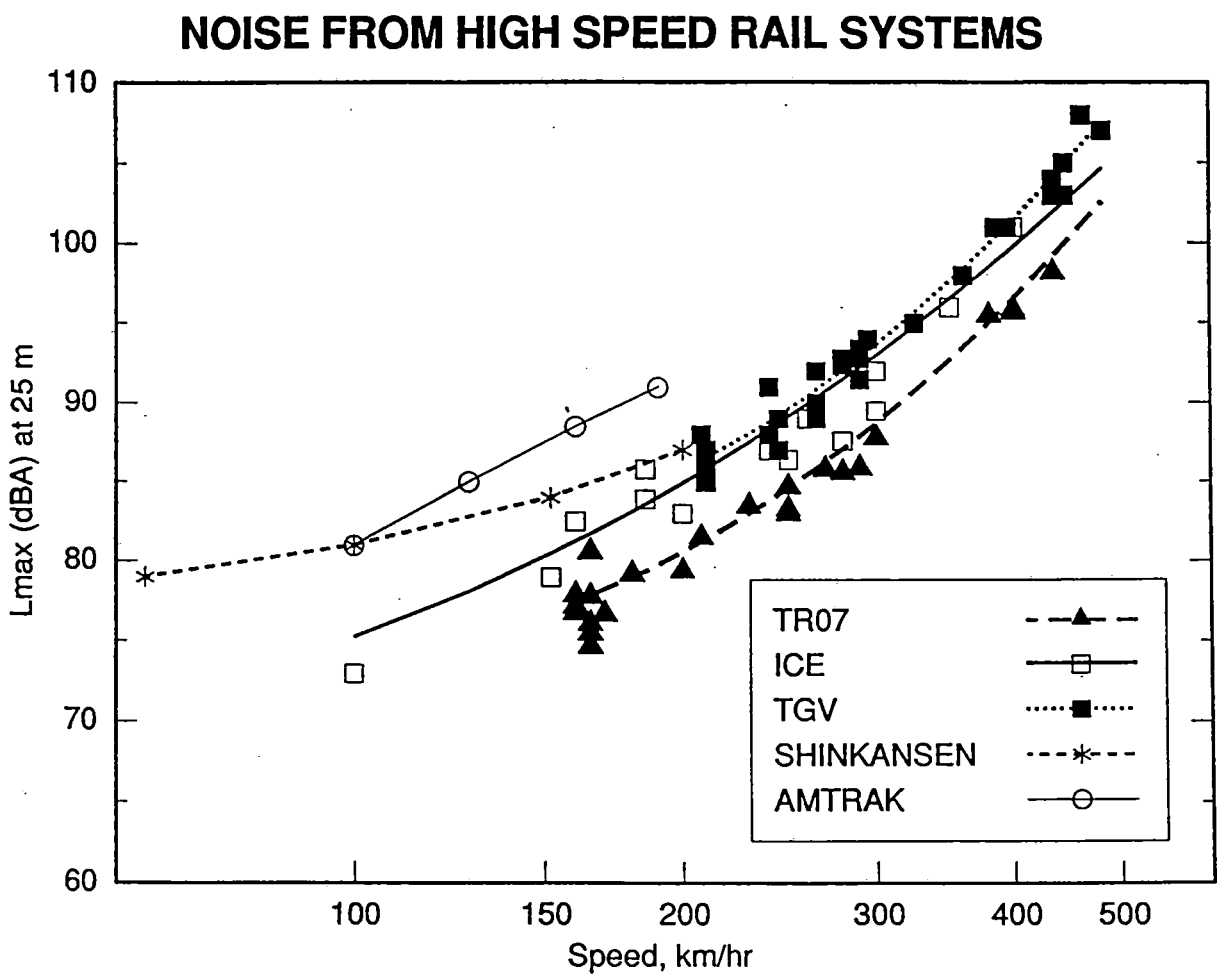


Figure 4. Noise from Maglev and Electrically Powered High Speed Rail Systems

2.3 Noise Spectra

The noise advantage of maglev shown in Figure 4 may be related to the lack of wheel/rail contribution. An example of the difference in sound spectra between a maglev and wheeled trains at high speed is shown in Figure 5. The one-third octave band spectra for the TGV, the ICE and the TR 07 are shown for the same speed, 290 Km/hr (81 m/sec).* These data are taken from measurements of TGV and ICE trains at-grade and TR07 on concrete elevated structure. The mid-frequency portion of the spectra from 160 Hz to 1250 Hz are similar for all three trains. But the major difference shows up in the frequency bands below 160 Hz and above 1250 Hz; clearly, the TGV and ICE trains have more sound energy in these parts of the spectrum at this speed. As speed increases, however, the sound energy associated with wheel/rail noise in the bands above 1250 Hz will increase according to a 30 log (speed) relationship, whereas the sound energy associated with aeroacoustic sources in the mid-frequencies (160 Hz to 1250 Hz) will increase at the greater rate of 60 to 80 log (speed). Therefore, as speed increases the mid-frequencies will dominate for all trains, whether maglev or wheel/rail, and the A-weighted sound levels should approach the same values.

In conclusion, it is in the high frequencies and the very low frequencies that maglev has a noise advantage over its current wheel/rail competitors. The mid-frequency aeroacoustic sounds are similar.

* The time over which these spectra are averaged is unknown; long averaging times tend to smooth out characteristic peaks in a spectrum which makes it difficult to diagnose specific sound sources. Another problem with interpretation of spectra from very fast trains is the smearing of peaks due to Doppler effect. Methods exist for obtaining de-Dopplerized spectra, but it is doubtful they were used in obtaining the spectra shown in Figure 5.

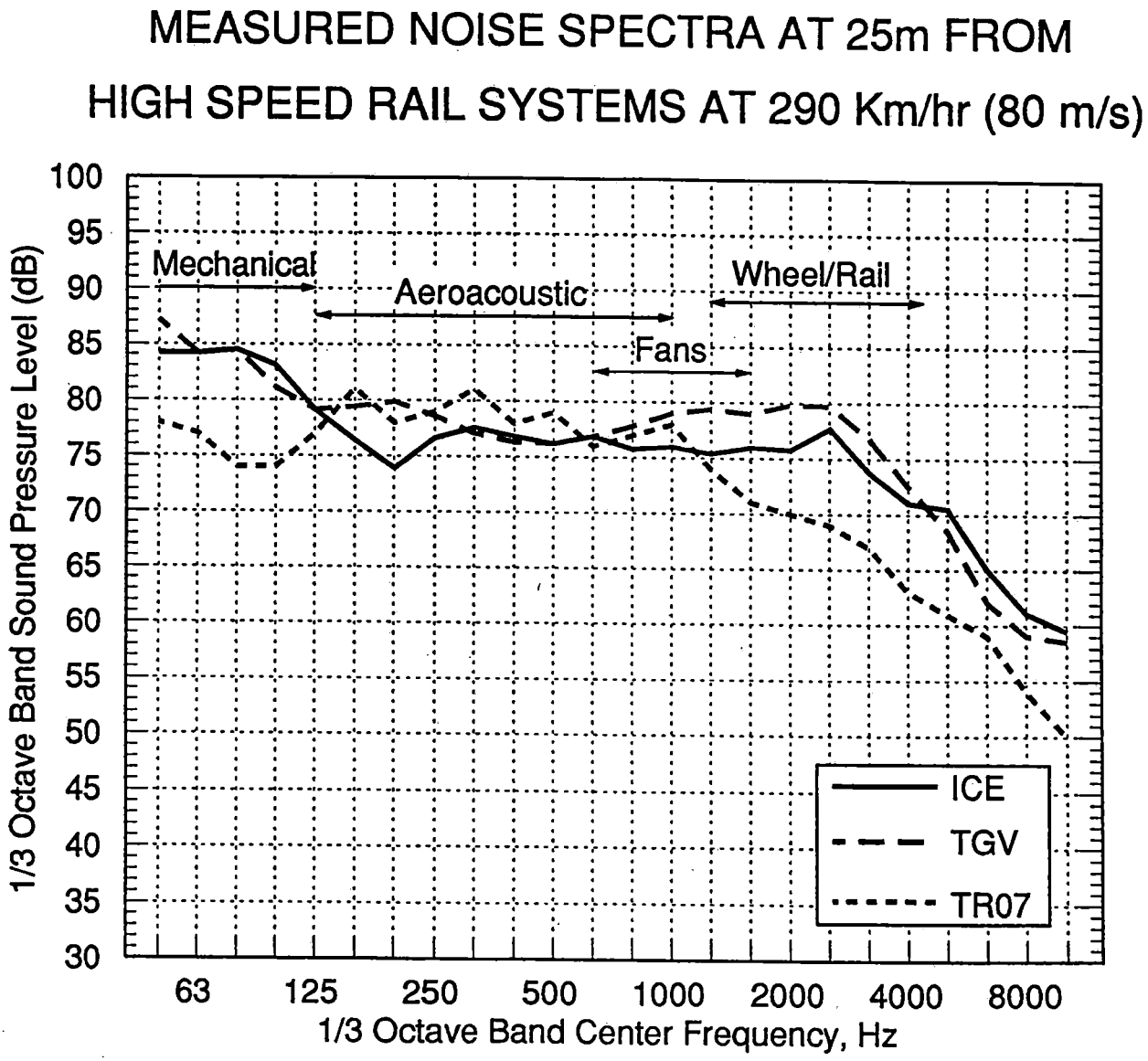


Figure 5. Noise Spectra from Maglev and High Speed Rail Systems at 290 Km/hr (Ref.2)

2.4 Normalized Sound Exposure Level

Perhaps more revealing than the data presented in the foregoing is a comparison of the sound energy emitted by maglev with that from other high speed trains. The metric used in such a comparison is the Sound Exposure Level (SEL) which expresses the sound energy from a single event, such as the passby of a train, normalized to a one-second duration. By further correcting for train length, one obtains a measure of the sound energy emitted by a unit length of the train, for example, the equivalent of the length of one car. The resulting metric is called the "normalized SEL." Normalized SEL's obtained from measurements of passby equivalent energy levels from TR 07, TGV and ICE (Ref. 2) are plotted for an equivalent vehicle length of 25 m in Figure 6. Despite the lack of a wide range of speeds of ICE and TGV, the trend is apparent. The data cluster along a common line with relatively little scatter, indicating that there is no significant difference in sound energies per unit length emitted by maglev on elevated structure and steel/wheel systems at-grade over the speed range of 165 Km/hr (46 m/sec) to 400 Km/hr (111 m/sec).

The normalized SEL curve follows a 40 log (speed) relationship, whereas the Lmax curve increases by 60 log (speed) in this speed range. The difference may be related to the way in which speed affects:

1. the exposure of a passby (Noise exposure metrics have an inverse relationship with velocity.), and

2. the spectrum (Doppler effect and convective augmentation shifts frequencies and levels upward in the forward direction, thereby increasing the A-weighted Lmax more than the total energy of the passby.)

The result that normalized SEL from maglev and conventional trains are the same has important implications in considering the environmental noise impacts of alternative systems. The SEL is the basic descriptor for noise sources in prediction models for environmental noise. The relation between "normalized SEL" developed here and SEL depends on the length of the train:

$$\text{SEL} = \text{"normalized SEL"} + 10 \log_{10} (\text{length}/ 25), \text{ dBA},$$

where train length is expressed in meters.

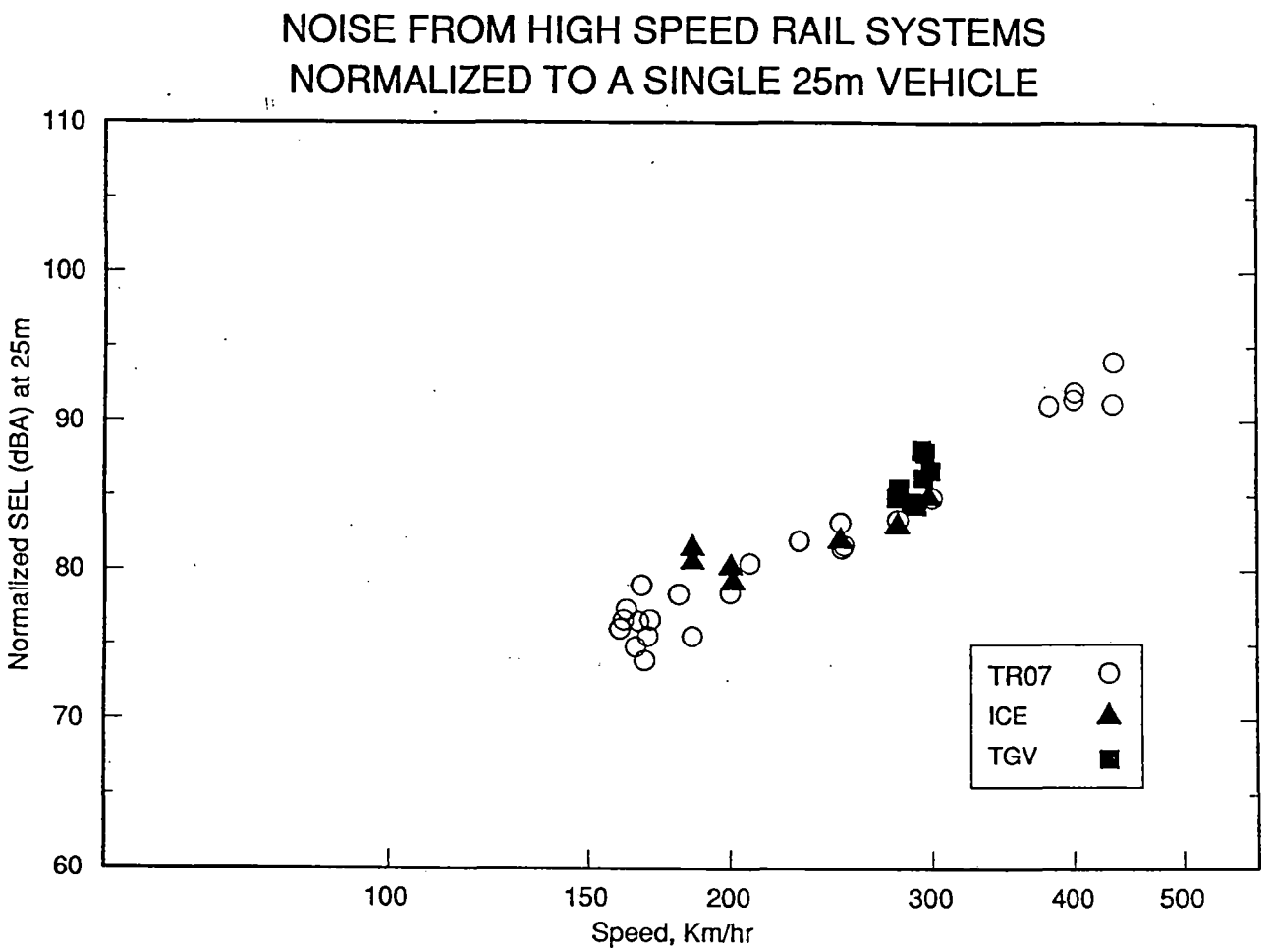


Figure 6. Sound Exposure Levels Normalized to Single 25m Vehicles

3. QUANTIFICATION OF THE ENVIRONMENTAL NOISE ISSUE

Noise criteria have not been established that apply directly to maglev or other high speed rail systems. Typically the lead agency for the mode of interest will have specific noise criteria which apply to the environmental impact of the transportation sources under its purview. In this case the U.S. Environmental Protection Agency has established noise limits on stationary and moving locomotives and moving railcars[5], but these standards were designed for freight train operations with noise levels set for diesel-electric locomotives and freight cars. Other modal agencies of the Department of Transportation have adopted similar specialized noise standards, none of which apply directly to a high speed surface transportation mode. Under Task 2 of the current maglev noise contract** HMMH will review existing noise criteria and propose modifications where necessary to apply to maglev operations. At this time the best we can do is to present a preliminary quantification of the potential environmental problem. The following discussion of criteria is intended only to provide that initial quantification.

3.1 Noise Criteria

As mentioned above, there are no authorized noise standards that apply specifically to maglev operations. Perhaps the closest environmental noise criteria are the newly proposed noise criteria for the Urban Mass Transportation Administration (UMTA)[6]. These criteria are based on population surveys leading to an estimation of the number of people highly annoyed as a function of Day-Night Sound Level, Ldn. Three levels of severity of noise impact are defined by the two curves which are depicted in Figure 7. Below the lower curve, a proposed project is considered to have no noise impact for noise-sensitive land use categories. Project noise above the upper curve is considered to cause Severe Impact for all land use categories. Severe noise impacts are considered "significant" as this term is used in the National Environmental Policy Act (NEPA) and its implementing regulations. Between the two curves the proposed project is judged to have an impact, though not severe. Whether the noise impact is determined "significant" in the context of NEPA will depend on a number of factors, including the types of land use affected. Mitigation will be be required for severely impacted properties, and may be required for impacted properties.

** Contract No. DTFR 53-91-C-0074, BAA No. 191

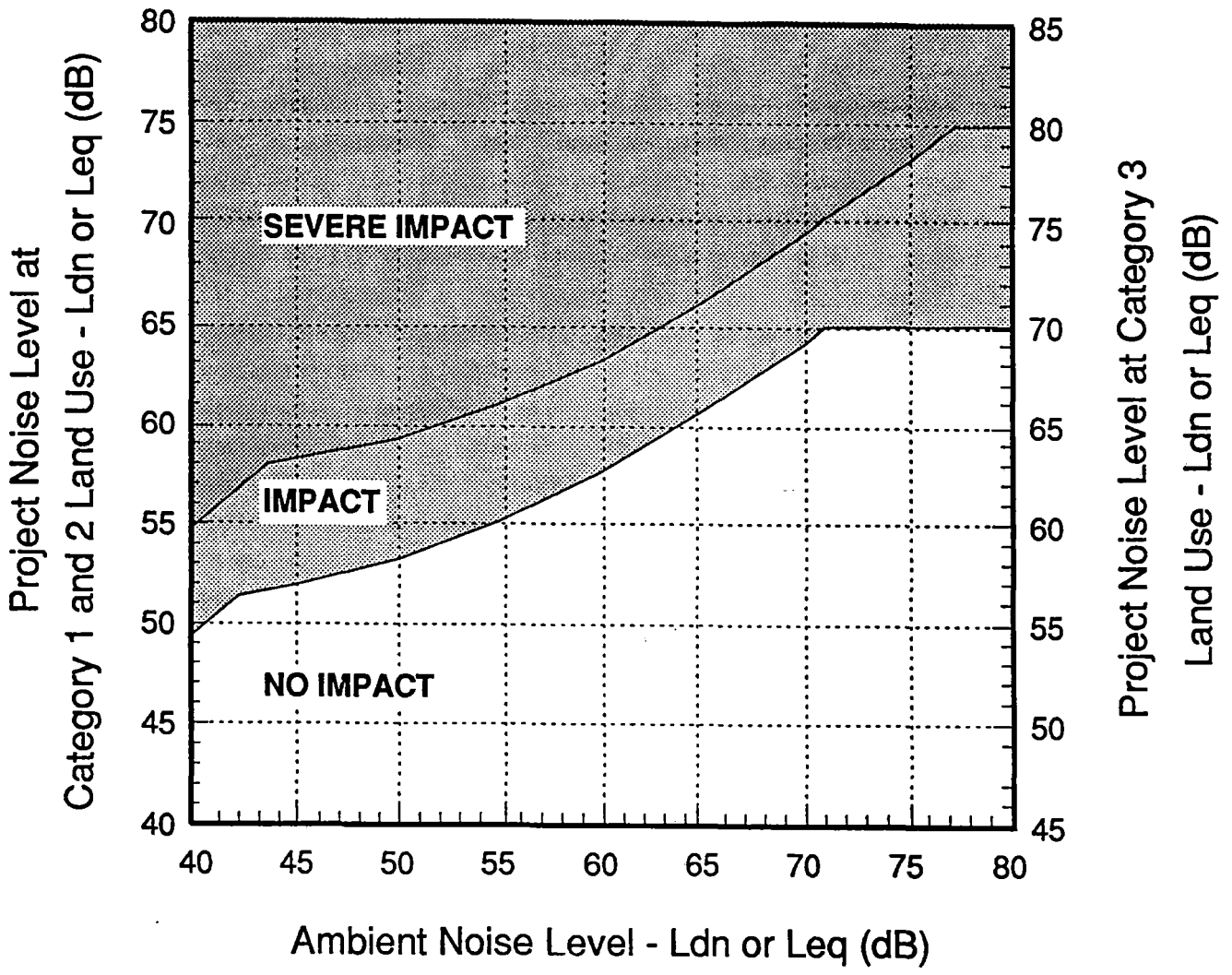


Figure 7. Proposed UMTA Noise Impact Criteria (Ref.6)

The proposed UMTA criteria are based on the following concept: For a known existing ambient noise level, the predicted future noise level can be rated according to its expected reaction from the public. These criteria were intended for application to urban mass transportation systems characterized by many passbys in each hour, but at speeds generally no greater than 130 Km/hr (36 m/sec). Consequently, they may require modifications for direct applicability to maglev in a number of ways, for example:

1. Correction factor to account for startle reactions to sudden onset of high noise levels as may occur during a passby of a nearby maglev train.

2. Correction factor to account for perceptions of the sound quality and spectral characteristics of maglev.

3. Consideration of maximum sound levels of single events.

These are among the factors that will be assessed in continuing tasks of this contract. Nevertheless, application of the proposed UMTA noise criteria can be made with some degree of confidence that they will provide a preliminary quantification of the expected reaction of the public to the introduction of a new surface transportation noise source like maglev.

In addition to assessment based on long term changes in the noise environment as expressed by the Ldn, it is worth exploring the potential for annoyance from single events. Again, no Federally authorized standards have been developed for maximum passby levels. The American Public Transit Association[7] (APTA) has recommended a maximum nighttime noise level of 75 dBA at 15 m or the nearest house, whichever is further, for a single passby of an urban transit train in a high density single family residential area (80 dBA for multi-family dwellings). Japan National Railroad (JNR) experienced overwhelming public outcry from the introduction of the Shinkansen with noise levels shown in Figure 4; in response, the Japanese Transport Ministry established Lmax goals of 70 dBA for residential areas. Moreover, the French National Railroad has introduced noise mitigation measures for the TGV-Atlantique Line in residential areas. As shown in Figure 4, the maximum noise levels from single passbys of a maglev at high speed are higher than those of APTA's criteria, higher than those of Shinkansen, and are comparable to those of the TGV. These comparisons suggest that the single passby level from maglev may be high enough to cause complaints.

3.2 Noise Impact Assessment

For our example of noise impact from the introduction of maglev as it exists now without noise mitigation, we will look at two levels of public transportation service, the existing passenger train service provided in the Northeast Corridor between Boston and New York and between New York and Washington, D.C. UMTA criteria are based on Ldn which requires consideration of the noise from train passbys during daytime (7 am to 10 pm) and nighttime (10 pm to 7 am) hours separately. A train departing during the daytime at one location could arrive at another location during the nighttime. As a result, noise exposure must be assessed on a site-specific basis depending on the volume of train traffic and the time of day it occurs. Our examples will be based on selected points along the selected routes: a suburb of Boston and a suburb of Washington. Residences in these areas are located typically as close as 30 m from existing tracks. Urban or suburban residential areas with population density of 2,500 people per square kilometer are expected to have an existing ambient Ldn of 60 dBA[8]. With that number as the existing ambient, the proposed UMTA criteria show that Ldn's of 58 dBA and 63 dBA from a new source would cause "impact" and "severe impact," respectively.

Boston to New York - Current 1991 Northeast Corridor service between Boston and New York has a total of 16 day and 6 night trains passing through the suburbs of Boston. Assuming the same frequency and a similar level of service could be provided by 10 - vehicle maglev trains with the same schedule, the normalized SEL from Figure 6 is converted to SEL for a 10-car train at a speed of 400 Km/hr (111 m/sec) using the equation given in Section 2.4. Ldn is subsequently obtained from spreading out the energy contained in 22 total events over 24 hours, but first adding 10 dB to each nighttime event (passbys). The result is an Ldn of 70 dBA at 25 m. The line labeled "Boston suburb" in Figure 8 illustrates the distances from the guideway that would considered to be impacted using the UMTA criteria. The noise propagation with distance over open terrain was taken from actual measurements at the TR 07 test track (Ref. 2). Impact would occur for any residence within 145 m of the guideway and severe impact would result for any residence within 70 m. At the severe impact distance of 70 m, each passby would have a maximum passby level of 86 dBA lasting for 2.25 seconds; at 145 m, the maximum level would be 78 dBA. Both of these maximums are well above the APTA Guidelines for urban transit systems.

New York to Washington - Current 1991 Northeast Corridor service between New York and Washington has a total of 54 day and 10 night trains passing through the suburbs of Washington. Assuming the same frequency and a similar level of service could be provided by 10 - vehicle maglev trains with the same schedule, the normalized SEL is converted first to SEL, then to Ldn using the same procedure as in the previous example. The result is an Ldn of 74

dBA at 25 m. The line labeled "Washington suburb" in Figure 8 illustrates the distances from the guideway that would considered to be impacted using the UMTA criteria. Impact would occur for any residence within 215 m from the guideway and severe impact would occur within 109 m. Each passby would have a maximum passby level of 75 dBA at the "impact distance" of 215 m and 81 dBA at the "severe impact distance" of 109 m. Again, both of these maximum levels are above those recommended for urban transit by APTA.

3.3 Summary of Maglev Noise Issues Related to the Community

From the foregoing it is evident that without noise control, noise levels from a high speed maglev system could be great enough to evoke negative public reaction. The evidence is as follows:

1. Maximum noise levels from high speed passbys of a vehicle like the TR 07 exceed those which are known to cause negative public reaction.

2. Long term noise exposure from regularly scheduled high speed maglev passenger service could cause impact in heavily traveled, high speed corridors in residential areas.

Consequently, special consideration should be given to testing and incorporating noise control techniques at the design stage of any system that is adopted. In order to understand what is causing the noise, we look into the mechanisms for generating noise in the next section.

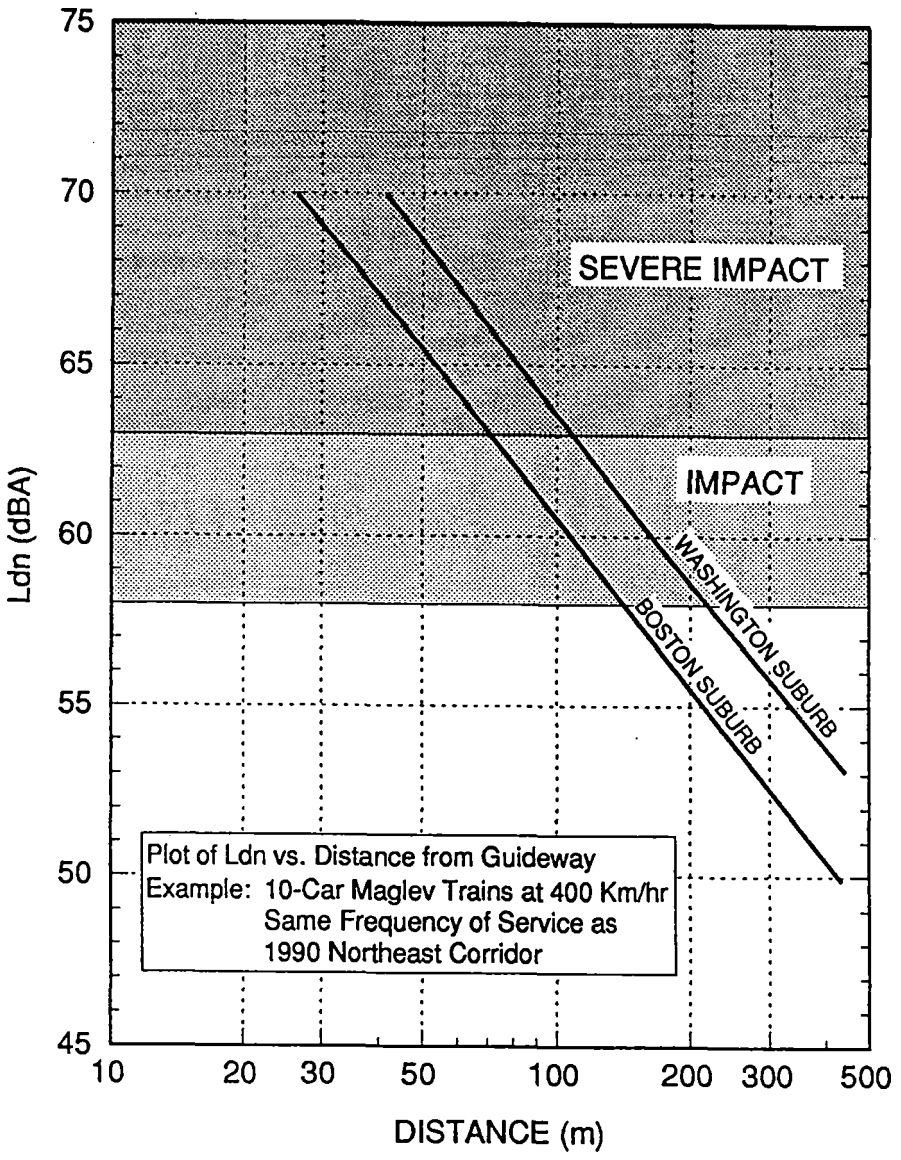


Figure 8. Ldn vs. Distance for Examples

4. MAGLEV NOISE SOURCES

Taking a cue from the aircraft industry which has made great improvements in controlling aircraft noise, it is clear that understanding the noise generation mechanisms is the first step in designing mitigation into a new maglev system. Noise sources may originate from the propulsion system, mechanical/structural interactions and aerodynamic forces. Defining the contributions from each source makes a difference in determining the appropriate design mitigation measures. This section discusses the basic mechanisms involved in the likely sources for a maglev system. Some results from noise measurements on the TransRapid system are available; we refer to them frequently to understand general trends. Often these results are from single point microphone measurements (Figure 9) which describe the integrated effect of a passby, but which are inadequate for detailed diagnosis of sound sources. Consequently, results from specialized tests will be necessary in order to differentiate among the many sources that are involved in noise generation from a high speed vehicle and its guideway. This section discusses the various mechanisms that may be involved in the generation of sound, with resolution among sources to be determined by further testing. A strategy for future testing programs is included in Section 5 of this report with more details to follow in the Task 4 Report under this contract.

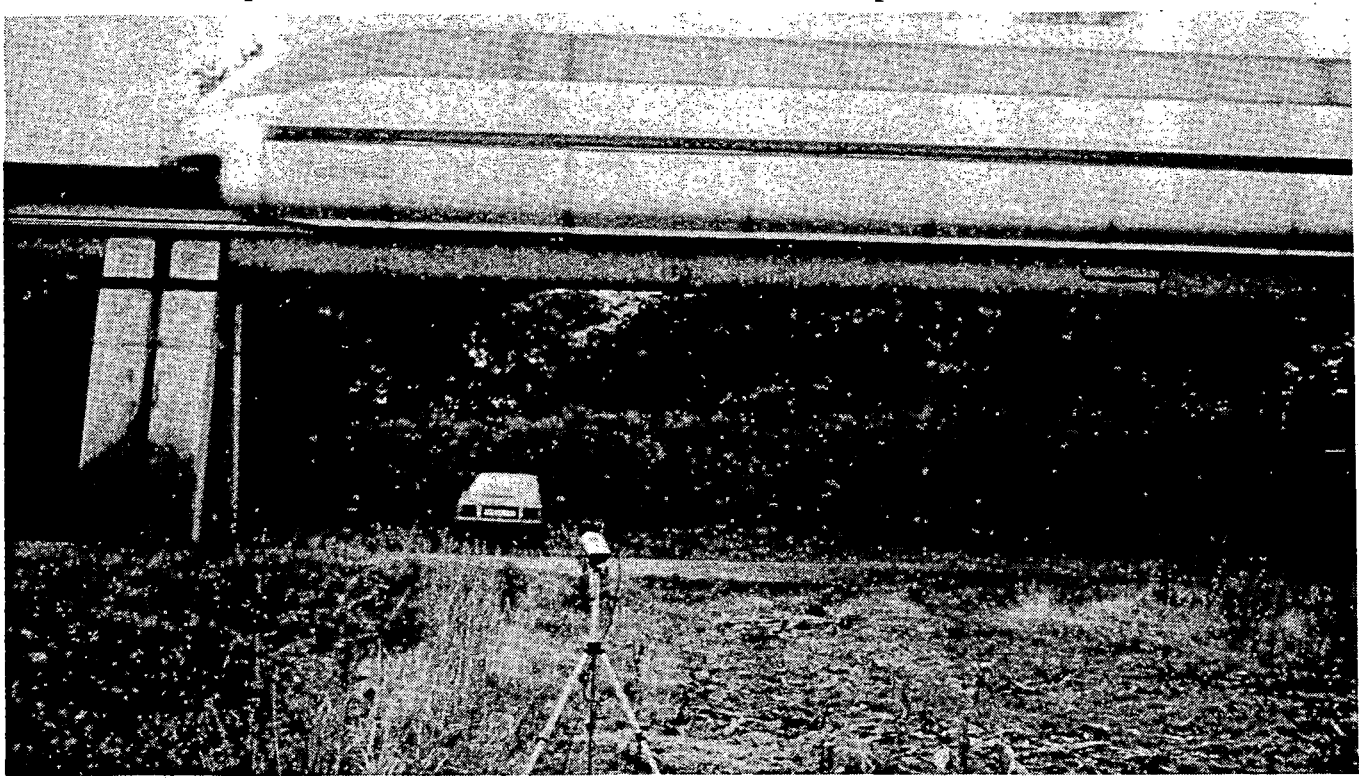


Figure 9. Single Point Noise Measurement of TR 07 at Emsland Test Track

4.1 Overall Noise Relationships

Noise from the TR 07 maglev system increases with speed according to the plot in Figure 10. Many of the acoustic sources associated with moving vehicles are known to be speed dependent, with speed raised to some power. For example, later in this section some aeroacoustic sources are related to speed raised to the sixth power. Typically, noise from a train at low speed is proportional to the third power of speed; at high speeds it is proportional to the sixth power of speed; and at very high speeds could be proportional to the eighth power of speed. In a plot of noise vs. the logarithm of speed, such exponential relationships become straight lines. Consequently, noise from transportation sources is more commonly depicted in terms of straight line segments -- noise level as a linear function of log (speed). For this set of data two lines can be used to represent the data. Two lines are shown in Figure 10 which represent least mean square fits to the data:

$$L_{max} = 80 + 37 \log (speed/200), \text{ dBA for speed} < 250 \text{ Km/hr (69 m/sec), and}$$

$$L_{max} = 83 + 62 \log (speed/250), \text{ dBA for speed} > 250 \text{ Km/hr (69 m/sec).}$$

The curves indicate noise sources that dominate fall into at least two speed regimes, a low speed regime where the noise is proportional to the third or fourth power of speed and a higher speed regime where noise is proportional to the sixth power of speed. Although it is not known exactly which sources dominate these speed ranges, a typical mechanical/structural noise source would have a 30 log (speed) relationship and a typical set of aeroacoustic sources would have a 60 log (speed) relationship. Therefore, the pattern of maglev noise vs. speed fits a recognizable pattern, but the actual mechanism of noise generation can not be known without further research.

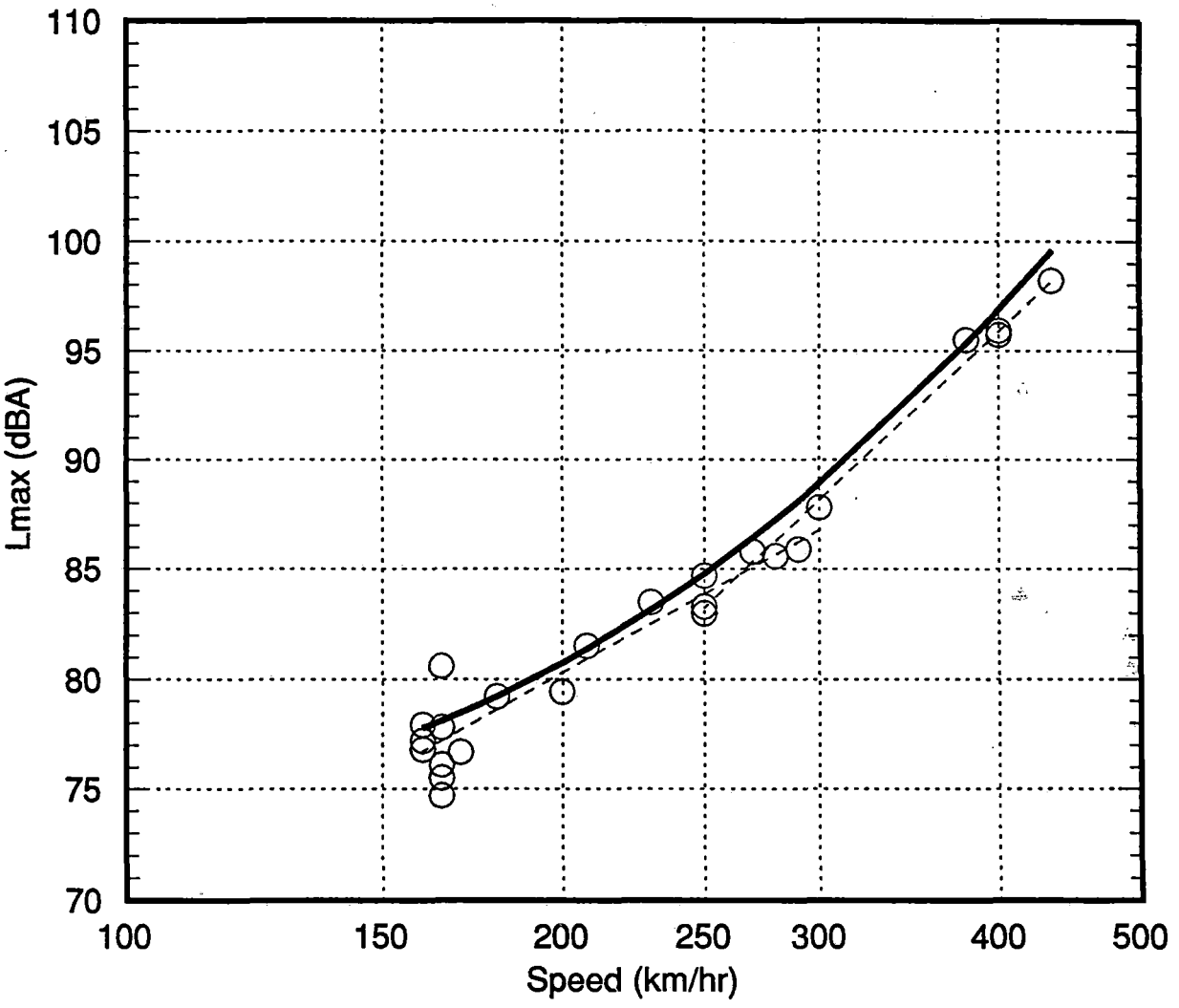


Figure 10. Lmax vs. Speed for TR 07 at 25 meters

4.2 Propulsion Sources

Unlike most forms of transportation, maglev noise does not appear to be dominated by propulsion noise. Some of the sources include the electromagnets, control system and cooling fans. Electromagnets are basically quiet, although noise can be generated by magnetostriction, coil oscillation, and pole passing.

Magnetostriction occurs when the iron core of a magnet undergoes changes in flux -- it shrinks or expands as the magnet polarization oscillates around its mean value. Anything that is attached to these magnets will experience a vibration as the magnet goes through dimensional changes. These changes occur at twice the line frequency of the alternating current resulting in a fundamental of 120 Hz in the U.S. and 100 Hz in Europe. Because the process is non-linear, the vibration is rich in higher harmonics. The vibrations can result in a tonal sound radiation at the fundamental frequency and its harmonics from any attached structure.

Coil noise is generated by the vibration of the coil surrounding the iron core of a magnet when electromagnetic forces alternatively attract and repel the windings in the presence of magnetic flux. This turns out to be a fairly weak sound source; its fundamental occurs at twice the line frequency (120 Hz in the U.S.).

Pole passing noise occurs as a result of variation in intensity of magnetic forces as the moving magnet poles pass over the fixed poles in the guideway. Alternating forces cause vibrations in the stator frames attached to the guideway. This source is tonal and can be significant in the low- to mid-frequency range. An example of stator magnets is shown in Figure 11, where the underside of the TR 07 guideway is shown. The pole pitch of the guideway stator is 0.258 m. Prominent in the figure are the stator cores, three per pole, which result in a "slot passing frequency" of three times the pole passing frequency. For this configuration, the pole passing frequency can be determined as a function of speed as follows:

$$\text{Pole Passing Frequency} = \text{Speed (m/s)}/0.258 \text{ m}, \quad \text{Hz.}$$

For example, at a speed of 245 Km/hr (68 m/sec), pole passing frequency is 263 Hz. Figure 12 shows a one-third octave band spectrum of the TR 07 measured by HMMH indicating a significant peak in the 250 Hz band containing that frequency for 245 Km/hr (68 m/s). A peak at the slot passing frequency is also evident in the 800 Hz band.

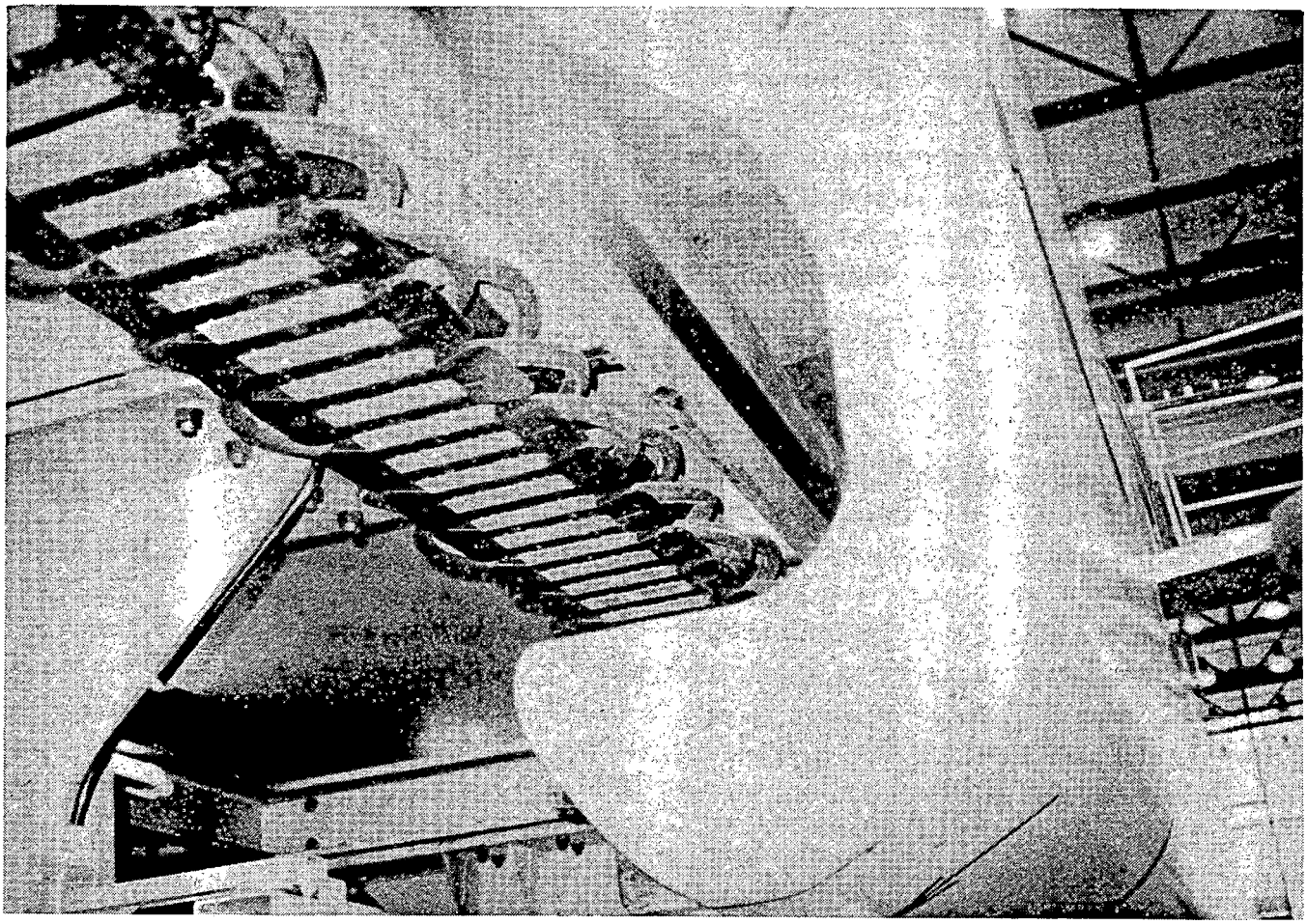


Figure 11. Underside of TR 07 Guideway Showing Magnets

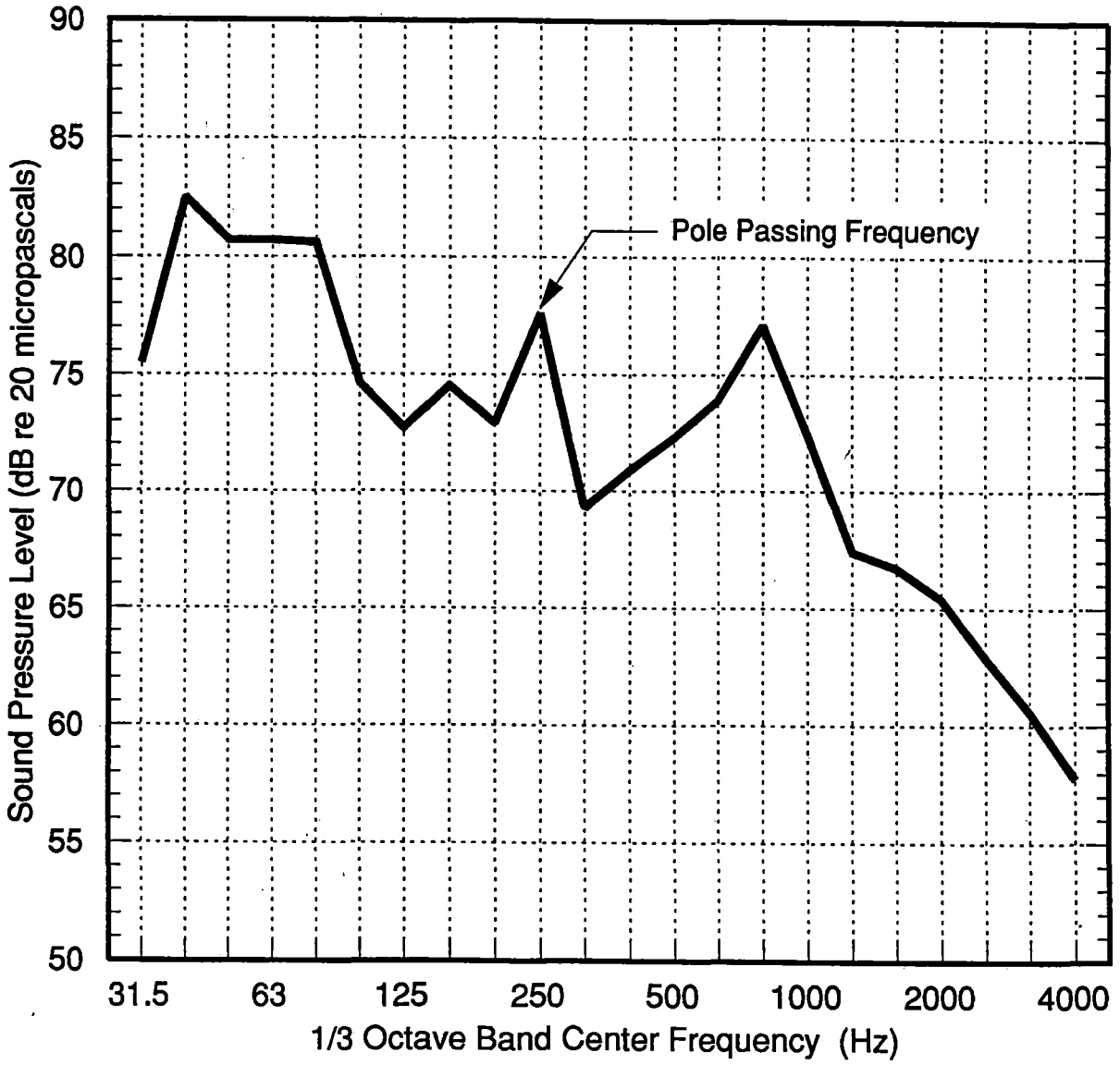


Figure 12. TR 07 Noise Spectrum at 245 Km/hr, 25 m Distance (HMMH data)

4.3 Mechanical/Structure Sources

Noise from the maglev system includes contribution from sources of mechanical and structural origin. These sources are associated with guideway and vehicle vibrations and they appear to dominate the total noise from the system at speeds below about 250 Km/hr (70 m/sec).

4.3.1 Noise from the Guideway

Noise is generated by vibrations of the guideway structure as the vehicle travels over it. At low speeds the electrodynamic levitation (EDL) technology employs wheels which roll directly on guideway support surfaces, and at high speeds, both EDL and electromagnetic levitation (EML) technologies load each guideway span with the weight of the vehicle despite the appearance of "floating" over it. The sudden on- and off-load of the vehicle on a guideway segment causes a dynamic response in the span, causing it to vibrate in various modes, each with their own natural frequencies depending on the size and configuration of the structure. Moreover, during the time of traverse of the segment, the magnetic support system of the vehicle generates pulse-loads at the pole passing frequency on the stator magnets attached to the guideway. There may also be higher frequency force inputs associated with the control system responsible for positioning the vehicle.

A structure such as a maglev guideway radiates sound because it is made up of beams and plates, each of which can vibrate at characteristic frequencies and each of which has a large surface area which makes for efficient sound radiation. Sound power radiated from a vibrating plate is related to the area and the averaged mean square vibration velocity of that plate. For a given force, the vibration velocity of a plate or beam depends on a number of qualities, including:

- material- some materials have more damping than others, e.g. concrete vs. steel,
- dimensions - natural frequencies are largely determined by the length and width of plates and beams, and
- attachments - stiffening ribs, composite layers, and joints with other beams and plates affect the vibrational response of a structural element.

The lowest frequency is likely to be the span's fundamental bending frequency, generally in the 2Hz to 5 Hz range. Although these frequencies are well below the audible frequency range,

there is evidence that infrasonic waves are undesirable.[9]

Other natural modes of beams and plates are excited by vibrational forces. When these structural elements are exposed to forces containing a wide range of frequencies, they respond strongly at their natural modes, many of which are in the audible range, and less strongly but still significantly at the forcing frequencies. For example, when a maglev vehicle passes the stator poles, it inputs a force at the pole passing frequency. The plates and girders to which the stators are attached will respond to the force input. If a modal resonance frequency is near the driving frequency, the response in terms of mean square velocity of the structure will be great and the sound radiation will be enhanced.

Figures 13, 14 and 15 are examples of a steel section, a concrete section and a (steel) switch of the existing maglev test guideway in Emsland, Germany. Spans are typically 25 m, with 2.8 m wide guideway running surfaces. Girders of a variety of steel and concrete box beam sections are being tested at the track. Pictured in Figure 13 is a steel triangular cross section, 2.8 m wide and 2.2 m deep. Figure 14 is a concrete triangular section, 2.8m wide and 1.8 m deep. Figure 15 is a photograph of a hydraulically actuated steel beam which bends over a length of 130 m to serve as a switch from one concrete guideway to another.

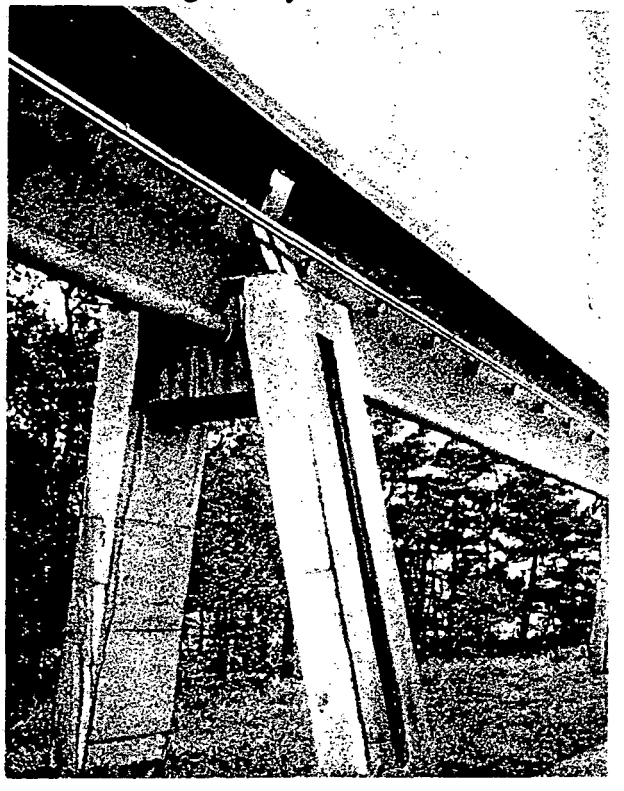


Figure 13. Photograph of Steel Guideway at Emsland Test Track, Germany

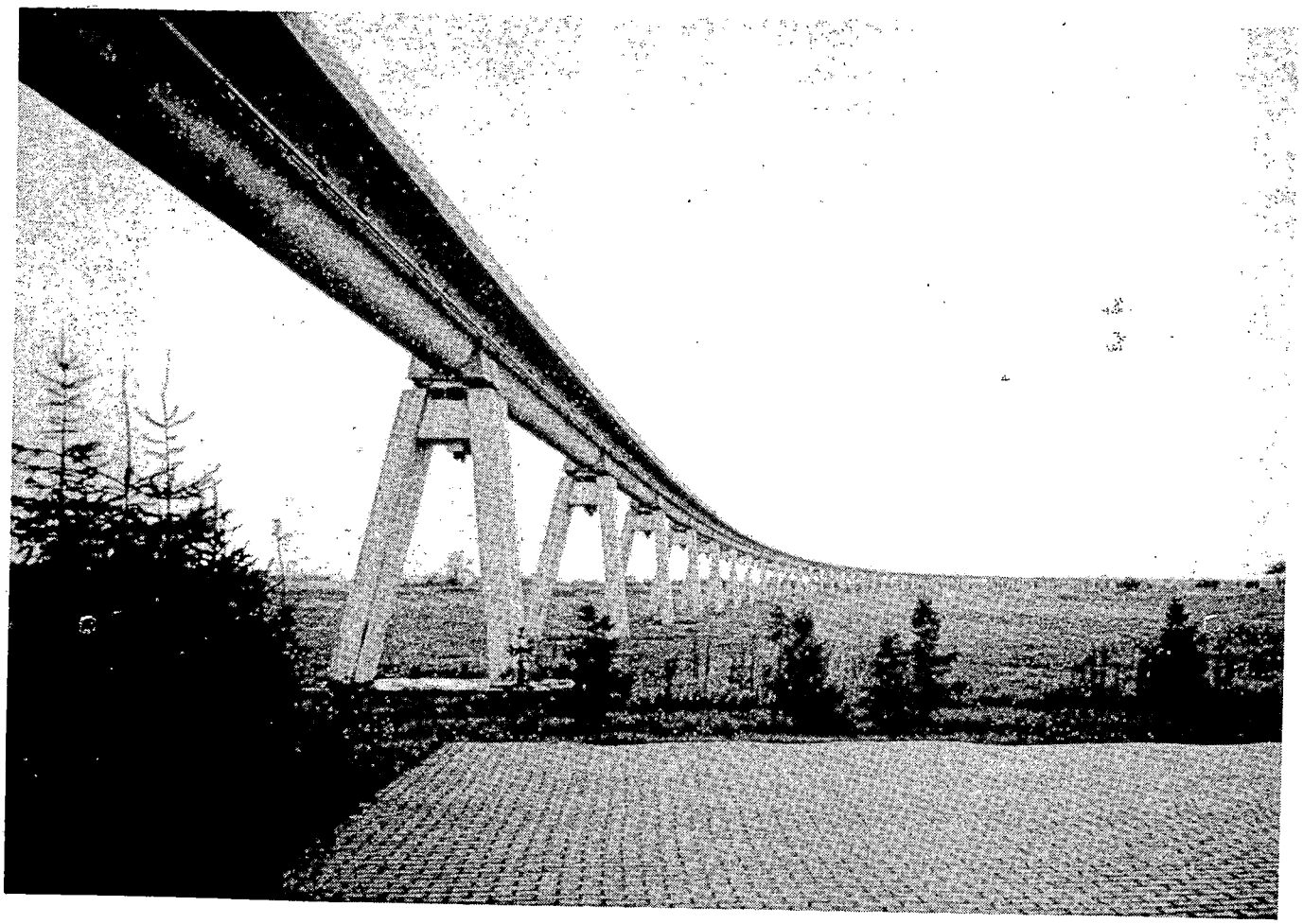


Figure 14. Photograph of Concrete Guideway at Emsland Test Track, Germany

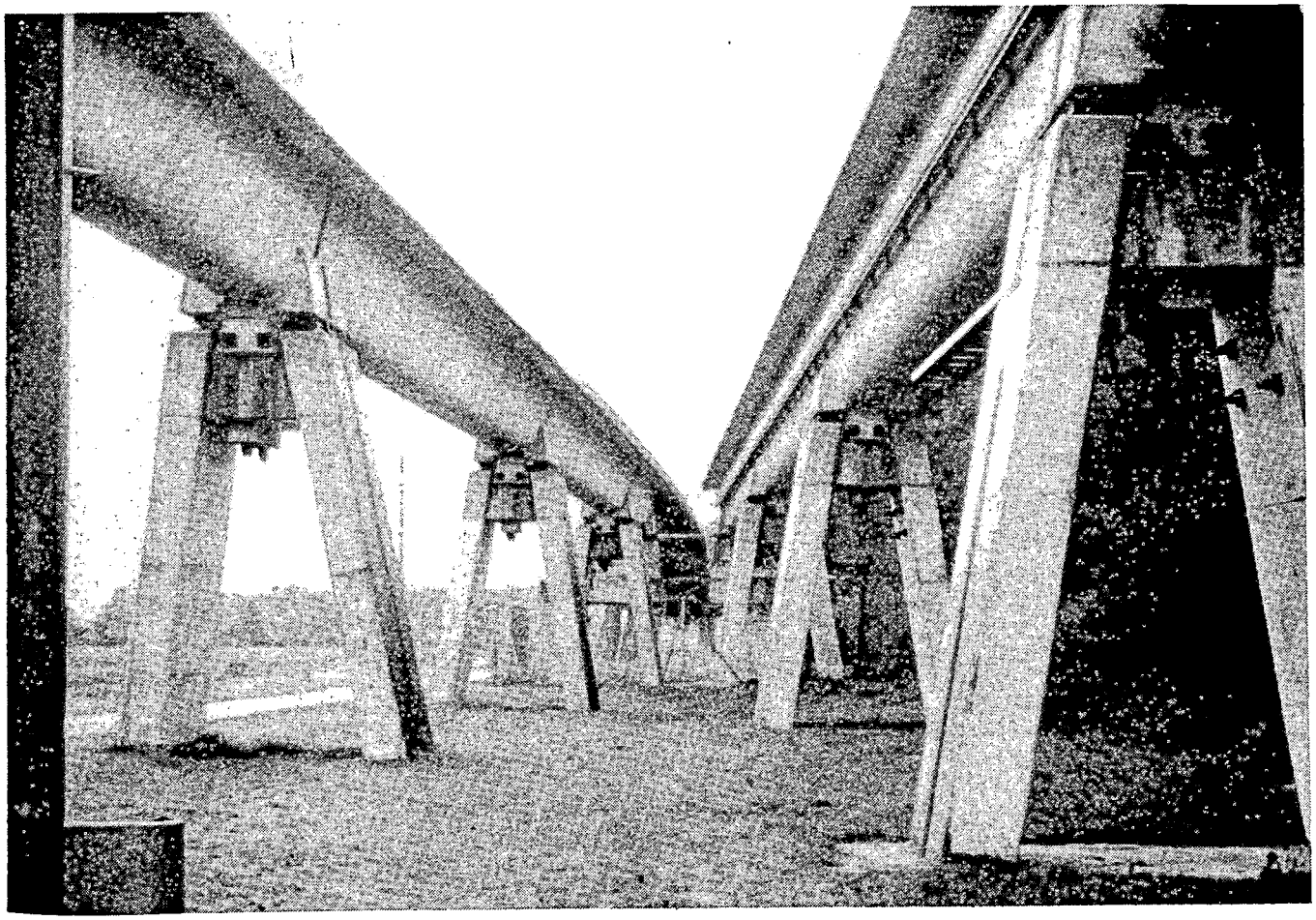


Figure 15. Photograph of Switch at Emsland Test Track, Germany

Because it has less material damping, a steel structure is likely to have increased vibration amplitudes at resonances and corresponding greater sound radiation than a concrete structure for the same force inputs. Noise measurements of the TR 07 on different guideway types were conducted at the Emsland Test Track by Industrieanlagen Betriebsgesellschaft (IABG). Noise as a function of speed is shown in Figure 16. As expected, the steel guideway elements, spans and switch, radiate more noise than do concrete elements, although all the curves appear to coalesce at speeds of 350 Km/hr (97 m/sec) and greater. For example, the figure shows that at a speed of 200 Km/hr (55 m/sec) the maglev on a steel structure has a maximum level of 5 dBA greater than it has on a concrete guideway.

Figure 17 compares the sound spectra at 200 Km/hr (55 m/sec) for these two guideway configurations and shows where the 5 dBA difference appears. The steel guideway has significantly greater sound energy in the mid-frequencies (400 Hz to 2000 Hz) which are important in determining the A-weighted sound level. It also has significantly greater energy at very low frequencies (31.5 Hz to 100 Hz) which are important in excitation of building structures, although these frequencies are de-emphasized in the A-weighted spectrum. The sound energy at the pole passing frequency in the 200 Hz band is significant; it is noteworthy that the levels are nearly identical for both guideway types. The origin of the dominant peaks in the spectra, at 630 Hz for the concrete guideway and 800 Hz for the steel guideway are unknown.

One of the noise control treatments typically proposed for steel box beam girders on urban rail transit elevated structures is the addition of damping, which is very effective at the higher frequencies dominating the A-weighted sound level. Similarly, damping may help bring the steel guideway noise down to that of the concrete structure,

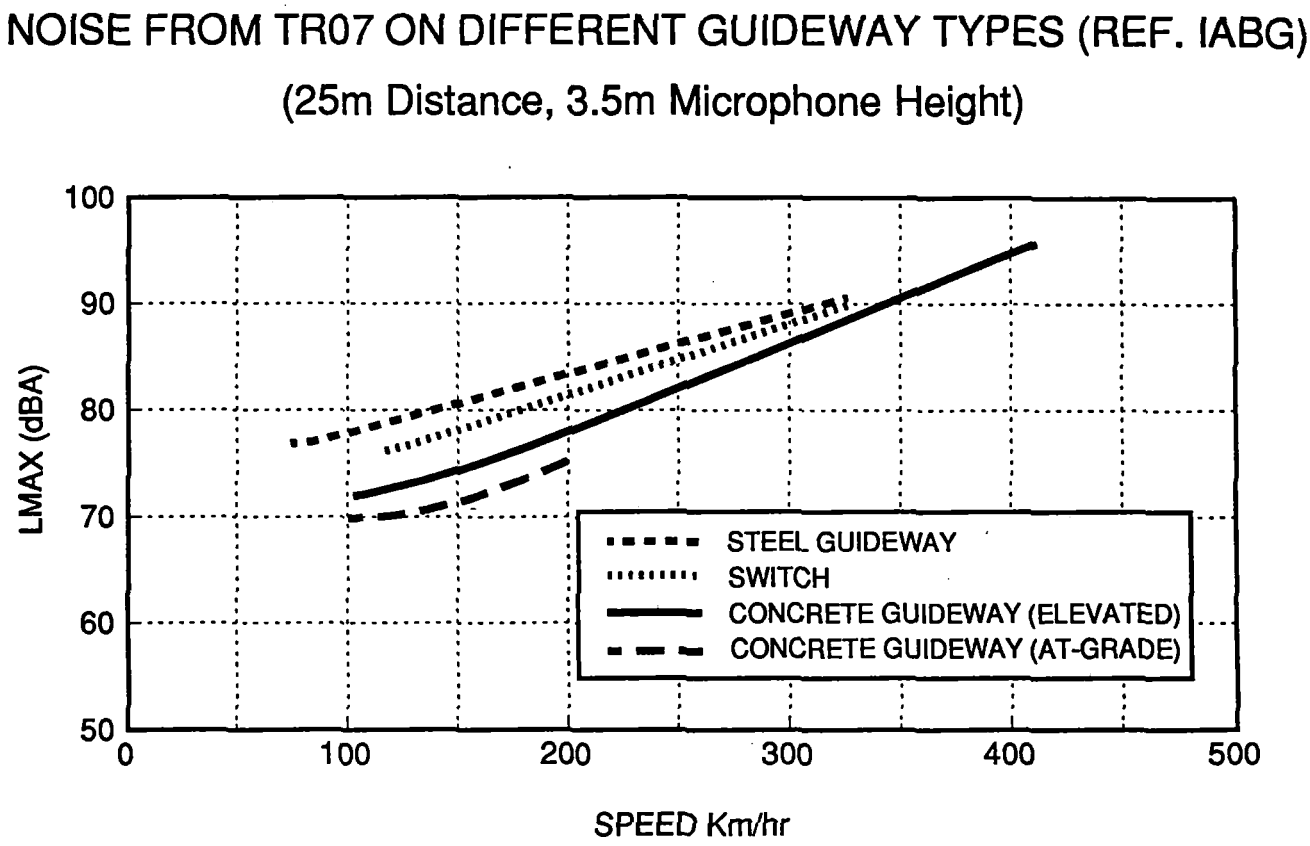


Figure 16. Noise from TR 07 on Different Guideway Types

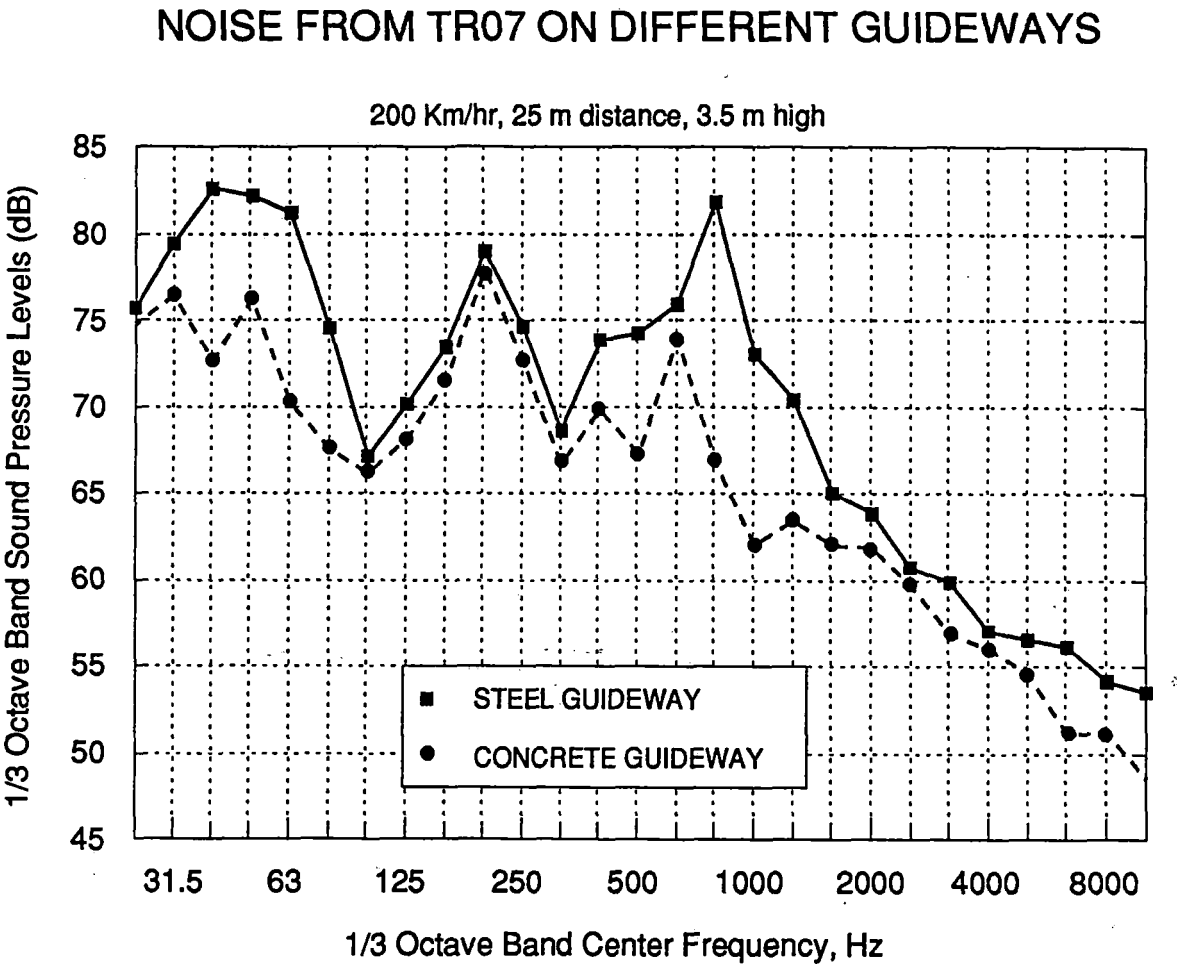


Figure 17. Noise Spectra of TR 07 on Different Guideways

4.3.2 Noise from the Vehicle Structure

The discussion in Section 4.3.1 concerning noise radiation from plates applies to the sound radiated from structure and body panels of the vehicle. Vibration of the external surface of the vehicle results in radiated sound at frequencies corresponding to both forced and resonant response of the panels. Among the force inputs that could cause radiation from the vehicle are:

- aerodynamic excitation,
- magnetostriction,
- coil oscillation and
- magnet gap variation at the pole passing frequency.

Aerodynamic excitation, such as caused by the turbulent boundary layer over the vehicle surface, is a candidate for structural sound re-radiation, as discussed in Section 4.4. Magnetostriction of the levitation and propulsion magnets is a source of vibration at twice the line frequency and higher harmonics; any structure that is attached to the magnets is subject to a forcing function from this source. Coil oscillation is a minor source of noise; it is generated when current-carrying coils of the electromagnets undergo oscillating forces when the alternating current passes through stray magnetic flux lines. The small movement of the coil components couples to the air and radiates as sound. A significant source of panel excitation occurs as the vehicle moves over the magnets in the guideway. The variation in the magnet gap causes vibrations as the moving poles pass over the stator poles at the pole passing frequency. This source is evident in every maglev spectrum, but it is not known if the noise is from the vehicle or from the guideway (or both).

4.4 Aeroacoustic Sources

The indication that noise from very high speed trains is of aerodynamic origin has focused interest on understanding the aeroacoustic sources that may be responsible for the very high noise levels. This section presents an overview of the aerodynamic generation of sound on a maglev vehicle and then looks at the characteristics of each of the likely sources. It is important to understand that the field of aeroacoustics is very complex; there are many different mechanisms that can result in similar noise characteristics and the researcher often has little data with which to work. Many of the hypotheses about dominant sources are based on circumstantial evidence from limited data. As research proceeds, however, the sources will become known and mitigation measures can be developed.

4.4.1 Overview of Aerodynamic Sound Generation

A maglev vehicle travelling at high speed causes unsteady disturbances in the surrounding air which generate fluctuating forces and/or pressure fields. These fluctuating forces and pressures along the body cause sound to be radiated either directly from the disturbance at the air flow-body interface or by vehicle panels caused to vibrate by these forces or pressures. This type of sound production is called aeroacoustic radiation and the sources are directly related to the aerodynamic disturbances.

On a high speed maglev there are many air flow disturbances which can cause noise. Figure 18 shows the major types of aeroacoustic mechanisms present on a high speed maglev system. Although an EML vehicle is displayed, the same mechanisms apply to an EDL system. As the nose of the body penetrates the surrounding air, noise can be generated from shear forces in the gap between the vehicle and the guideway, transition from laminar to turbulent flow over the top and sides, and flow separation at the nose and reattachment on the body. A maglev nose designed optimally from an aerodynamic point of view (low drag, no flow separation, streamlined, etc.) will serve to reduce the noise generated from the front section of the vehicle.

Slightly downstream of the nose, the turbulent boundary layer (TBL) becomes fully developed and imparts intense local pressure fluctuations normal to the body surface. Sound is generated directly from the fluctuating pressures driving on the external skin. Energy from the intense TBL pressure field is also accepted by the body and dissipated into travelling waves (bending, longitudinal and others) along the body. These bending waves produce sound either directly or upon encountering edges, ribs and other discontinuities within the body. This mechanism of sound generation is referred to as structural re-radiation from the TBL and is not solely an aerodynamic source since the sound radiation is also dependent on structural dynamics properties (material, damping, construction) of the body.

As the turbulent boundary layer encounters edges on a high speed vehicle, sound is generated efficiently. For example, for maglev trains of two or more vehicles, the joints between vehicles result in edges under the boundary layer. Also, a sharp edge may be present as the boundary layer departs from the rear of the train.

Other possible sources of aeroacoustic sound generation are flow cavity resonances, body roughness effects, leading edge effects of the nose penetrating the quiescent air and vortex flow associated with the interaction between the moving vehicle and fixed components of the guideway.

The overall effect of the aerodynamic forces on a vehicle contribute to the resistance of the air to the forward motion of the vehicle, called the drag. Research results show that drag of an airframe is related to the radiated noise; King reports the radiated sound pressure from an airframe in clean configuration to be proportional to the coefficient of drag raised to the 1.5 power.[10] Assuming results from airframe noise studies are applicable to maglev vehicles, this relationship suggests that a reduction in overall noise level can be attained by reducing the drag.

In the following sections, we present aeroacoustic sources as they relate to the observed sound radiation from a high speed vehicle.

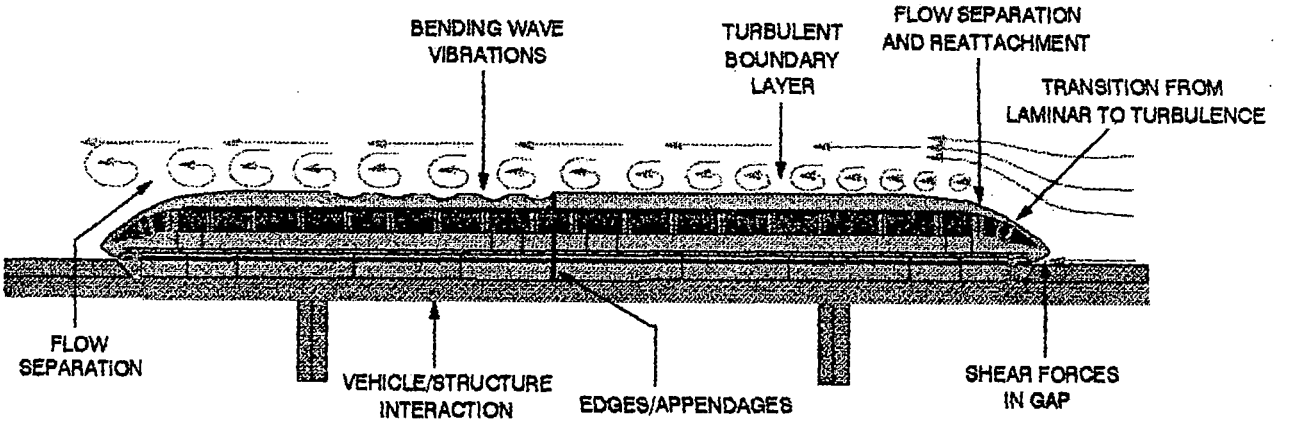


Figure 18. Aeroacoustic Sources on a Maglev System

4.4.2 Aeroacoustic Mechanisms at the Nose

As the vehicle travels at high speed, the flow disturbances begin at the nose. First, a turbulent shear layer develops in the gap where the leading edge of the nose approaches the guideway surfaces (deck and sidewalls). This shear layer is like a confined boundary layer and can radiate sound in a manner that is similar to the TBL direct radiation and structural re-radiation discussed below. However, since the shear layer is enclosed, it is less likely to be a strong radiator to the wayside unless there are openings in the bottom and sides of the guideway. It is likely to be a source of noise for the interior of the vehicle, however.

As the air flows over the top and sides of the vehicle, the boundary layer changes from laminar to turbulent. At the transition region from laminar to turbulent flow on the nose, large fluctuations of the boundary layer normal velocity component can penetrate the core region of the flow field and effectively radiate sound. These fluctuations are the result of the formation, growth and coalescence of turbulent spots in the transition region. A theory for sound radiation from the transition region by Lauchle[11] says that the sound power radiation is proportional to vehicle velocity raised to the exponent 7.5. As an example of the difficulty in sorting out aeroacoustic sources, we will later show that this relationship is very similar to acoustic radiation that would be expected from turbulent boundary layer direct radiation.

Also near the nose of the older TR 06 maglev vehicle (Figure 19), flow disturbances have been observed by Alscher at each side of the vehicle slightly downstream of the intersection of the nose and the guideway surface.[12] These disturbances are caused by flow separation and vortex reattachment. Alscher used directive microphone arrays to locate a very intense acoustic source a few meters downstream of the nose (see Figure 21 in Section 4.4.4). His wind tunnel measurements showed that the flow was severely separating at the crease between the main body and the magnet shrouds. The processes of flow separation, vortex generation and reattachment are significant sources of acoustic energy and should be avoided if at all possible. As a result of wind tunnel tests, the nose on the TR 07 was re-shaped to eliminate the crease and to extend the profile down to the guideway surface (Figure 20). The new shape of the nose resulted in a 6.3% reduction of drag, which according to King would reduce the noise by about 1 dB from the shape alone. Elimination of the vortices provides an additional noise reduction.

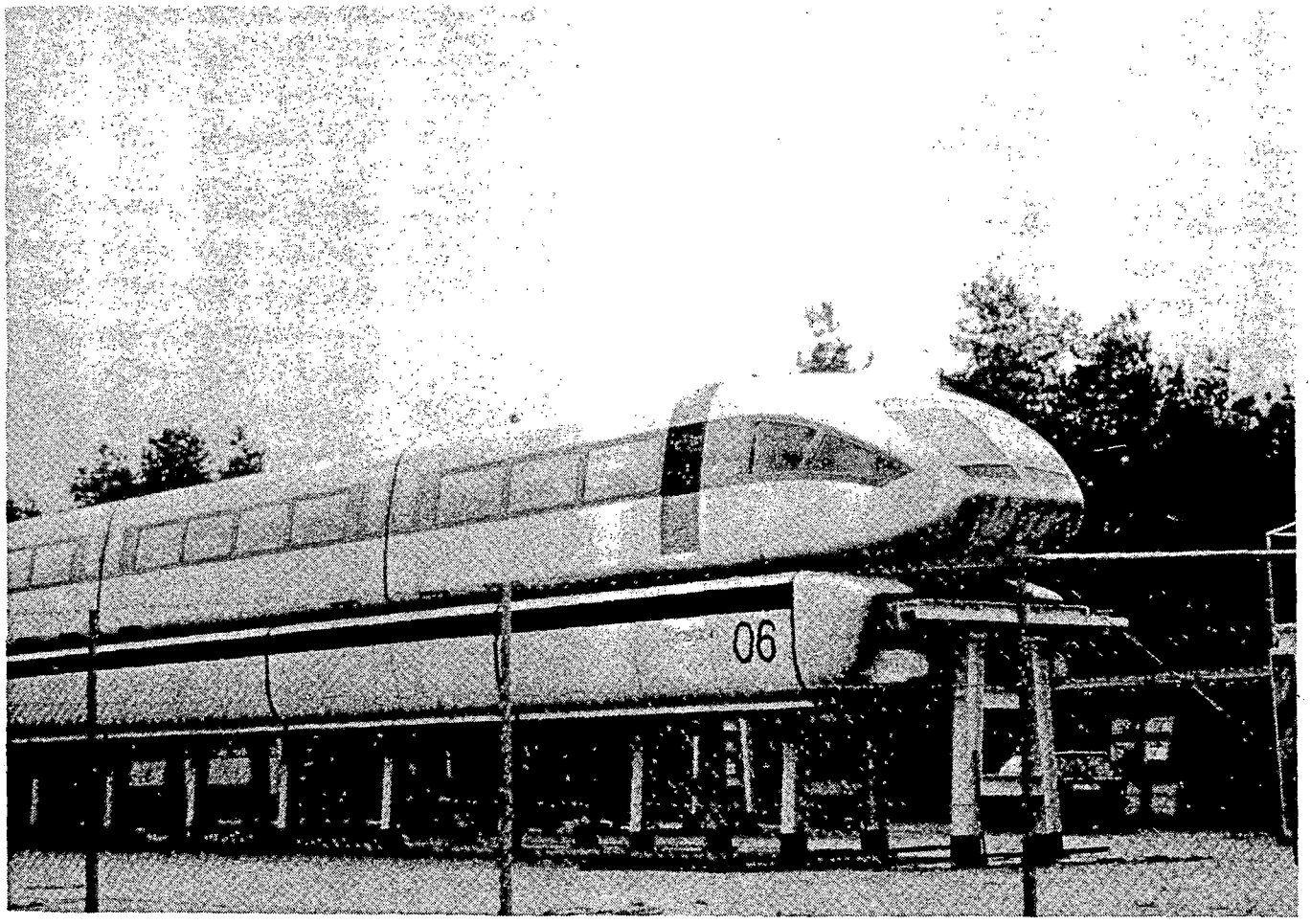


Figure 19. Photograph of Nose of TR 06

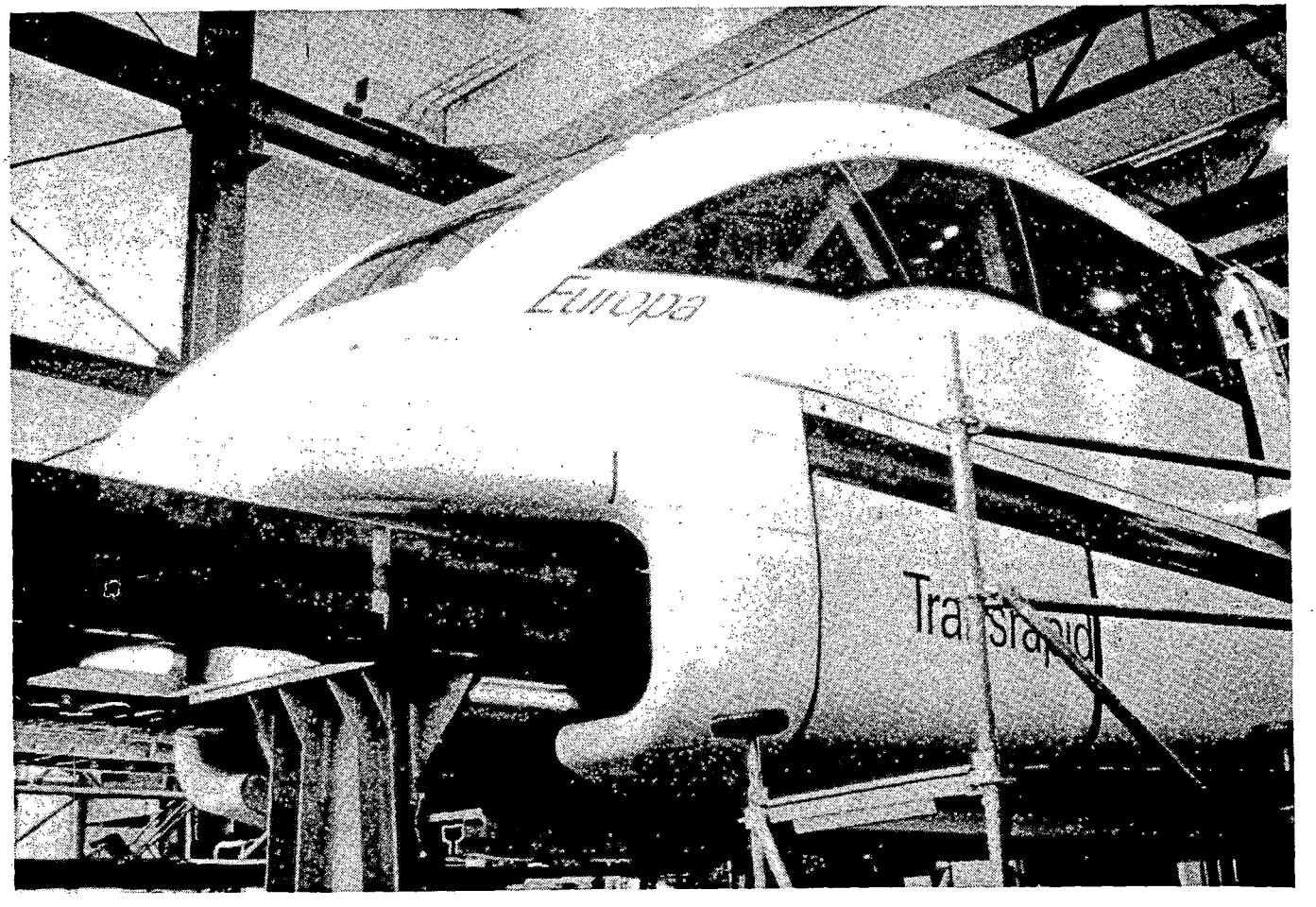


Figure 20. Photograph of Nose of TR 07

4.4.3 Aeroacoustic Mechanisms Related to the Turbulent Boundary Layer

The turbulent boundary layer has been found to be a major source of noise from high speed vehicles. Theories of the sound radiation directly from the turbulent boundary layer have been developed by Lord Rayleigh[13] , Lighthill[14], Ffowcs-Williams[15], and others. These theories suggest that for low Mach number flow, there are two boundary layer sources of sound: a stress field within the boundary layer and a stress field exciting the vehicle surface.

Boundary Layer Radiation. Lighthill showed that the stress field can be represented as a distribution of acoustic quadrupoles. His analysis suggests that the sound power radiated directly by the boundary layer stress field (independent of the surface boundary) is proportional to the 8th power of the velocity.

Ffowcs-Williams followed Lighthill's analysis with one in which the presence of a rigid surface acts as a sounding board thereby changing the quadrupoles into more efficient dipoles which radiate sound power at the 6th power of velocity. So now we have two possible mechanisms, one radiating at the 6th power and the other radiating at the 8th power of vehicle speed. There is some experimental evidence (e.g., Figure 4) that at high speeds, 300 Km/hr to 400 Km/hr (83 to 111 m/sec), noise from TBL has a 6th power dependency and at very high speeds, greater than 400 Km/hr (111 m/sec), the 8th power asserts itself.

The theoretical and experimental determination of turbulent boundary layer sound radiation over a smooth vehicle surface is very complex and there is no universal agreement about the theories and experiments at present. For example, King presents evidence that airframe noise could be expressed by acoustic dipoles covering the surface of the aircraft (Ref.9). However, Crighton[16] suggests that in the context of airframe noise (and by extension, within the context of maglev noise), quadrupole noise from boundary layers can be safely ignored relative to edge sources, other appendages, roughness elements and panel vibration.

Vehicle Surface Radiation. Crighton showed that the normal fluctuating surface stresses are strong enough to excite structural vibration which radiate sound as the waves in the structure encounter ribs, frames and other discontinuities, or radiate directly[17]. This suggests that panel vibration could be a significant source of vehicle noise.

In summary, we have two mechanisms when turbulent boundary layers are involved in the

generation of sound. The stresses in the boundary layer radiate sound directly according to either U^6 or U^8. In addition, the normal stresses of the boundary layer excite structural waves within the maglev vehicle which may re-radiate sound (from the body) directly or upon encountering structural discontinuities. At present there are many theories about aeroacoustic sources. Several models have been developed to explain observed results of the speed dependency of noise, but so far the actual sources remain unknown, primarily because many source combinations can result in the same far field results. Special measurement techniques exist to differentiate among the source components, but to date they have not been fully utilized.

4.4.4 Edge Noise Mechanisms

Edge noise is the result of sound scattering from the convection of the non-radiating turbulent pressures departing past the trailing edge of a rigid plane. The flow-edge interaction was first analytically derived by Ffowcs-Williams and Hall[18], followed by Howe's uniform theoretical approach to trailing edge noise radiation. Howe showed the speed dependence of the sound power radiated from edge sources to be proportional to the 5th power of speed[19].

An edge on a vehicle surface can be a powerful source of sound. For example, Figure 21 taken directly from Reference 12 shows the noise in the frequency range of 800 Hz to 1300 Hz radiated from points along the length of a two-vehicle maglev (the older TR 06) at a speed of 388 Km/hr (108 m/sec). Three maxima of noise are shown, related to noise generated at the nose, the joint between cars and the trailing edge. The peak associated with the nose dominates for the reasons discussed in Section 4.4.1 above. With a reshaped nose, this peak is likely to diminish, leaving the middle peak, which is caused by the edge formed by the joint between two cars, as shown in Figure 22 for a TransRapid vehicle.

The sound frequency produced by edge scattering can be related to the size of the boundary layer present at the edge and the vehicle velocity. The center frequency (f_c) of the peak acoustic energy is proportional to the speed and inversely proportional to the size of the boundary layer (usually described by the boundary layer thickness, δ^*). This relation is known as the classical Strouhal scaling where $f_c \sim U/\delta^*$.

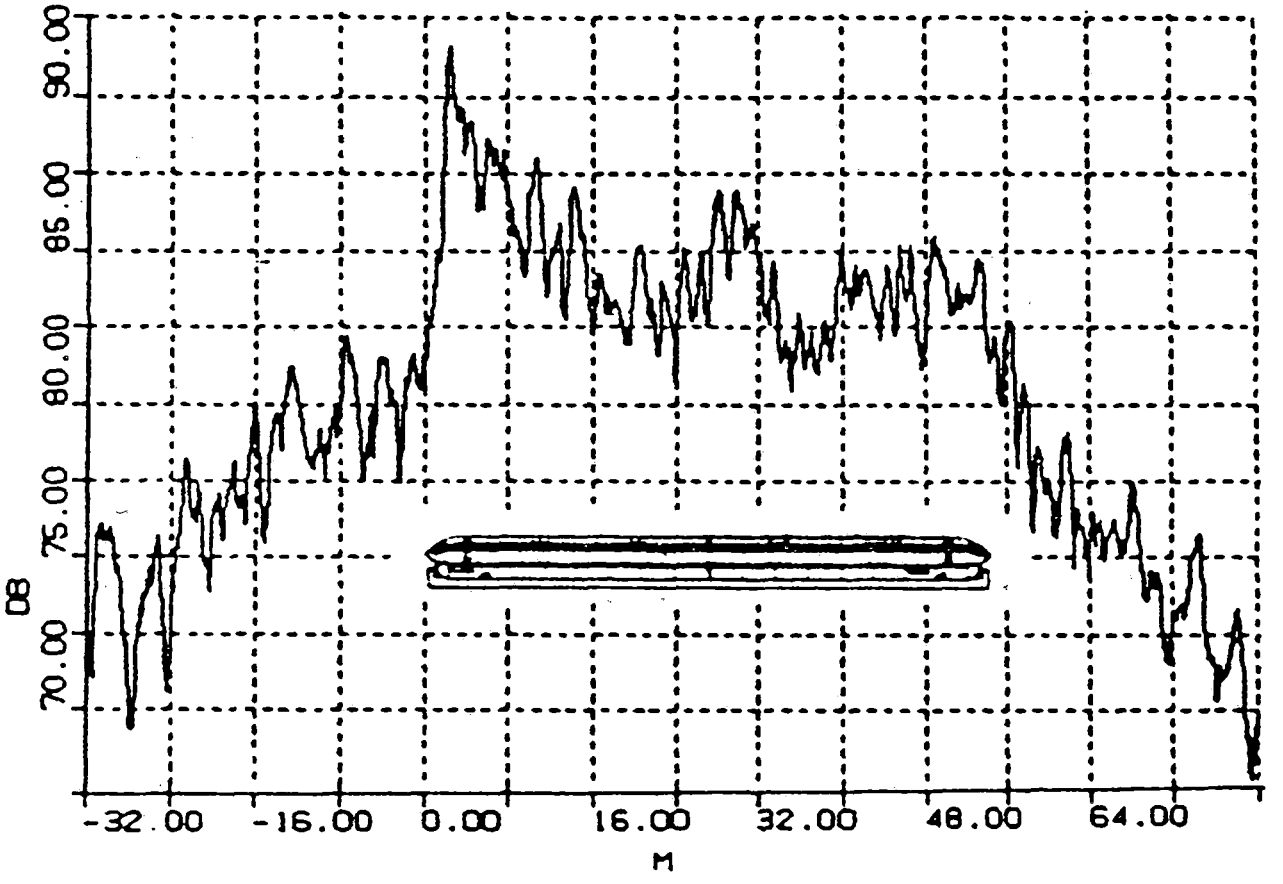


Figure 21. Longitudinal Noise Profile of TR 06 at 108 m/sec (from Ref. 12)

4.4.5 Other Mechanisms: Flow Cavity, Leading Edge and Cross Flow Effects

High speed flow over cutouts, cavities and guideway structural elements generate narrow (tonal) and broad band sound radiation. There are many theoretical and experimental studies identifying different types of flow cavity noise generation. It is very important to minimize these types of structural disturbances to the flow field.

Leading edge protuberances in the flow field can be a source of sound generation. This type of noise is similar to trailing edge noise and may occur on the nose of a Maglev or at the downstream leading edge gap between coaches. Presently, there are not much data available on this type of noise source.

The noise character of a long cylindrical vehicle like a train moving forward is also affected by slight lateral motions, cross wind gusts and even curves. Such cross flows can upset the boundary layer field over the surface of the vehicle, resulting in variations of the aeroacoustic sources. The consequences of cross flows may affect the repeatability of the sound.

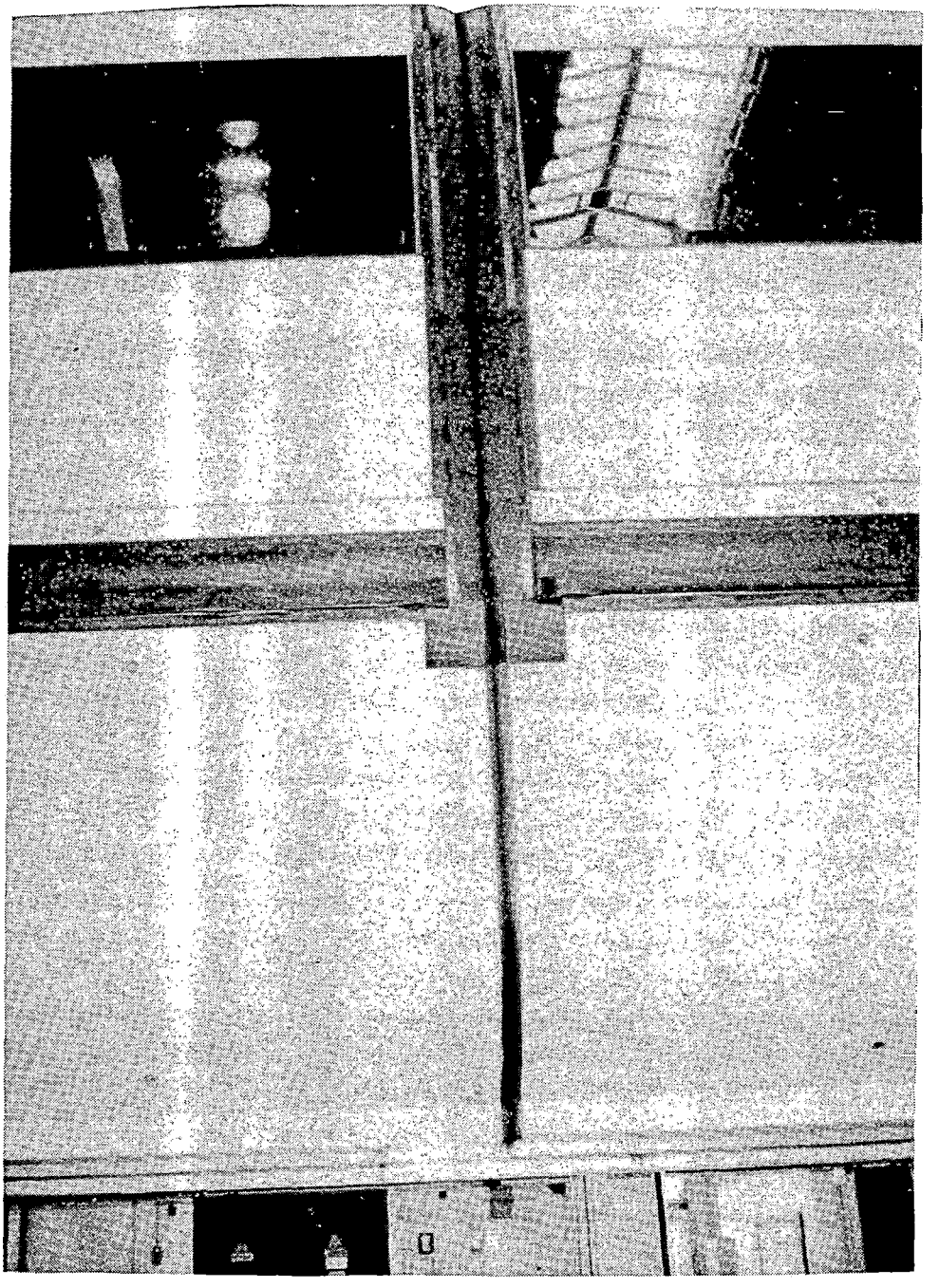


Figure 22. Photo of Joint between Two Vehicles

5. FUTURE RESEARCH PROGRAM

This report has summarized many of the available noise data from high speed trains in Europe and the TransRapid maglev system and has come to the following conclusions:

1. Without additional mitigation measures, noise from a current generation high speed maglev system could cause severe noise impacts in residential neighborhoods near the guideway. Negative public reaction could result in restrictions in locating new maglev rights-of-way, thereby adding to the cost of construction.

2. The evidence is overwhelming that aeroacoustic sources dominate the noise from both maglev and conventional high speed rail systems at speeds greater than approximately 250 Km/hr (69 m/sec).

3. Aeroacoustic noise may be a result of direct radiation from the airflow, or it may be a result of structural re-radiation from the vehicle, or both. Presently available data does not allow determination of the dominant sources.

4. Reduction of noise will be important in the design to counter the negative environmental effects of the introduction of a new maglev system. Control of these noise sources requires further research to gain an understanding of the various mechanisms that may be involved in the generation of sound.

These conclusions lead us toward a strategy for future research related to noise from a maglev system. Mechanical/structural noise tests are best performed on full scale facilities, but there are two approaches to conduct research on aeroacoustic problems; model testing in wind tunnels, or full scale (possibly quarter or half scale) on a test track. The choice revolves around the extent to which structural re-radiation is found to be important.

The model testing may be worth doing anyway, because the aerodynamic measurements will most likely be done in scale model wind tunnel testing. Model testing can give scale measurement of the direct radiation component and will provide an easier method for sorting out the various aeroacoustic mechanisms. On the other hand, if structural radiation is found to be important, then testing will be required on a full-, or nearly full-scale prototype. This will require one of two approaches:

1. Build a full scale maglev test facility in the U.S., along with a complete acoustical testing capability, or,

2. Gain access to a full scale test facility in another country.

The former would require a major U.S. commitment to maglev development, while the latter would involve a collaboration with Germany or Japan. A joint effort with one of the existing test programs would likely result in a more expedient resolution of the noise issues.

REFERENCES

1. Pennsylvania High Speed Intercity Rail Passenger Commission Final Report, Executive Summary, January 1990.

2. TUV Rheinland, "Gerauschmessungen an der Magnetschnellbahn TR 07 und an anderen Verkehrssystemen im Vergleich (Noise Measurements of the Maglev TR 07 and Other Transportation Systems in Comparison)," Institut fur Energietechnik und Umweltschutz, Bericht-Nr.: 933/329005/05-06, 4 July 1990.

3. Hanson, C.E. "Measurements of Noise from High Speed Electric Trains in the United States Northeast Railroad Corridor," J. Sound and Vibration, **66**(3), 469 - 471, 1979.

4. Anon. Shinkansen Noise, Japanese National Railways, August 1973.

5. U.S. Environmental Protection Agency, "Noise Emission Standards for Transportation Equipment; Interstate Rail Carriers." (40 CFR Part 201), 1980.

6. U.S. Department of Transportation, Urban Mass Transit Administration, "DRAFT: Guidance Manual for Transit Noise and Vibration Impact Assessment," Report No. UMTA-DC-08-9091-90-1, July 1990.

7. American Public Transit Association, 1981 Guidelines for Design of Rapid Transit Facilities, Section 2.7, "Noise and Vibration," 1981.

8. U.S. Environmental Protection Agency, "Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety," EPA No. 550/9-74-004, March 1974.

9. Bugliarello, G. et al, The Impact of Noise Pollution, Pergamon Press, New York, 1976.

10. King, W.F. "The Components of Wayside Noise Generated by High-Speed Tracked Vehicles," Proc. InterNoise 90, Gothenburg, Sweden, Aug 1990.

11. Lauchle, G.C., "Transition as a Source of Radiated Noise and Vibration," Proceedings of Flow-Induced Noise Due to Laminar-Turbulence Transition Process, American Society of Mechanical Engineers, Winter Annual Meeting, San Francisco, CA, Dec. 1990.

12. Alscher, Hans, "Aero-Acoustic Investigations of the Magnetic Train TRANSRAPID 06," Proceedings of Magnetically Levitated Systems and Linear Drives, The Institute of Electrical Engineers of Japan, Yokohama, Japan, July 1989.

13. Lord Rayleigh, Theory of Sound, Dover, New York, NY, 1945.

14. Lighthill, M.J., "On Sound Generated Aerodynamically, I: General Theory," Proc. Roy. Soc. (London), A211, 1952, pp. 564 - 587; "On Sound Generated Aerodynamically, II. Turbulence as a Source of Sound," ibid., A221, 1954, pp. 1 - 32.

15. Ffowcs-Williams, J.E., "Surface Pressure Fluctuations Induced by Boundary Layer Flow at Finite Mach Number," J. Fluid Mech., 22, 1965.

16. Crighton, D.G., "Airframe Noise," Aeroacoustics of Flight Vehicles: Theory and Practice, Volume I Noise Sources, edited by Harvey Hubbard, NASA Reference Publication 1258, vol. 1, WRDC Technical Report 90-3052, August, 1991.

17. Crighton, D.G., "Basic Principles of Aerodynamic Noise Generation," Prog. Aerosp. Sci., 16, 1975.

18. Ffowcs Williams, J.E. and Hall, L.H., "Aerodynamics Sound Generation by Turbulent Flow in the Vicinity of a Scattering Half Plane," J. Fluid Mech., 40, 1970.

19. Howe, M.S., "A Review of the Theory of Trailing Edge Noise," J. of Sound and Vibration, 61, 1978.

SECTION 2

NOISE CRITERIA FOR HIGH SPEED MAGLEV TRAINS

TABLE OF CONTENTS

LIST OF FIGURES

PREFACE

This report is the second of four reports to be prepared under U.S. Department of Transportation Contract # DTFR53-91-C-00074, "Noise from High Speed Magnetically Levitated Transportation Systems." The reports under this contract cover the following areas:

1. Characterization of Noise Sources
2. Noise Criteria for High Speed Maglev Systems
3. Preliminary Design Guidelines based on Noise Considerations
4. Recommendations for Acoustic Test Facility for Maglev Research.

The first report, HMMH Report No. 291550-1, presented information on the noise levels obtained from testing programs on the TransRapid system in Germany, described sources of noise from maglev systems, quantified the potential environmental noise impact from hypothetical systems installed in the United States, and identified further research needs for resolving the unknowns related to sound sources on high speed surface transportation vehicles.

This report presents information on the criteria recommended for use in evaluating noise impact from high speed maglev systems. These criteria describe the noise environment considered acceptable for specific land uses, depending on the ambient noise. These recommendations are based on the best available data related to transportation systems with noise characteristics similar to high speed maglev. As a result the conclusions must be considered based on circumstantial evidence until more definitive methods can be verified.

EXECUTIVE SUMMARY

The introduction of a new transportation system into a community generates concerns about the change in the noise environment brought about by the new source. When the new source has unique features, as does maglev, or when the community has not had prior exposure to a particular source, as will happen with a maglev system, the concerns are heightened. The unknown community reaction to such a potentially significant new development is not an acceptable risk for the builders and financiers during these times of environmental awareness. This report presents a means of rating the noise created by maglev in terms of the disturbance it creates.

Characteristics of Maglev Noise Resulting in Noise Impact

High speed maglev passbys are characterized by high noise levels and brief durations. Maximum noise levels at 25 meters from the guideway range from 77 dBA at 160 km/hr to 98 dBA at 435 km/hr for the TransRapid TR 07. Durations of the noise event depend on the length of the train and the distance of the receiver from the guideway, but for the two-car TR 07 at 435 km/hr, it takes only 3 seconds for the sound to rise and fall to 20 dB of the peak (Figure 1). The onset rate for the 435 km/hr signature is 21 dB per second. Onset rates greater than 15 dB per second are considered to cause "startle," worthy of a 5 dB penalty in an impact analysis. Onset rate depends on speed and distance from the guideway: fast rise times are associated with high speeds and/or close proximity to the guideway.

Maglev noise spectra are generally characterized by broad band distribution of frequencies. However, maglev has the potential of creating pure tones and these are considered to be especially annoying. Penalties of 5 dB are assigned to pure tone sources.

Community Noise Impact Criteria

Community response to noise is related to the total noise energy in a specified time period. The recommended community noise impact descriptor for maglev is the day-night sound level, Ldn, with an "onset rate adjustment" to account for fast rise times. Ldn is a single number "equivalent sound level" in dBA which contains the same acoustical energy as the actual time-varying noise pattern over 24 hours, but with a weighting factor of 10 dB applied to noise that occurs during the nighttime hours of 10 p.m. to 7 a.m. This unit

includes the noise effects that are considered to be most important to people's reactions to noise, including:

- Spectral content -- the A-weighting curve corresponds to the way in which humans interpret sound;
- Equal energy considerations -- trade-off between sound level and duration corresponds to 3 dB per doubling of duration; and
- Time of day sensitivity -- nighttime events receive an extra weighting of 10 dB.

The "onset rate adjustment" is an addition of 5 dB to sound exposure levels of each event that exhibits a rise time greater than 15 dB per second.

The noise impact criteria for maglev operations are based on comparison of the existing Ldn and future "onset rate adjusted Ldn" of the maglev operations. These criteria are identical to those proposed by the Federal Transit Administration for assessing noise impact from urban transit operations. The impact criteria are defined by two curves which allow increasing maglev noise levels as ambient noise increases up to a point, beyond which impact is determined based on maglev noise alone (Figure 11). Below the lower curve, a maglev system is considered to have no noise impact since, on the average, the introduction of the system will result in an insignificant increase in the number of people highly annoyed by the new noise. Maglev noise above the upper curve is considered to cause Severe Impact since a significant percentage of people would be highly annoyed by the new noise.

Between the two curves the proposed project is judged to have an impact, though not severe. The change in the cumulative noise level is noticeable to most people, but may not be sufficient to cause strong, adverse reactions from the community. In this transitional area, other project-specific factors must be considered to determine the magnitude of the impact and the need for mitigation, such as the predicted level of increase over existing noise levels and the types and numbers of noise-sensitive land uses affected.

The noise criteria and descriptors depend on land use, designated either Category 1, Category 2 or Category 3:

> Category 1 includes tracts of land where quiet is an essential element in their intended purpose, such as nationally significant historic sites or outdoor concert pavilion.

Category 2 includes residences and buildings where people sleep.

Category 3 includes institutional land uses with primarily daytime and evening use such as schools, churches and active parks.

The procedure for assessing impact is to determine the pre-project ambient noise level and the predicted maglev noise level at a given site, and to determine the impact by plotting these levels on the chart shown in Figure 11. The location of the plotted point in one of three impact ranges is an indication of the severity of the impact.

Example of Application Method

For the hypothetical direct replacement of Northeast Corridor service with 10-car maglev trains at 400 Km/hr in a Boston suburb, noise "Impact" would occur for any residence within 80 m of the guideway and "Severe Noise Impact" would occur for any residence within 40 m. In addition, the potential for startle would occur for any residence within 32 m of the guideway, due to onset rates in excess of 15 dB per second.

1. INTRODUCTION

1.1 Need for Noise Criteria for Maglev

The introduction of a new transportation system into a community generates concerns about the change in the noise environment brought about by the new source. When the new source has unique features, as does maglev, or when the community has not had prior exposure to a particular source, as will happen with a maglev system, the concerns are heightened. The unknown community reaction to such a potentially significant new development is not an acceptable risk for the builders and financiers during these times of environmental awareness. It is important to have a means of rating the noise created by maglev in terms of the disturbance it creates, in order to gauge the community response and to avoid unacceptable installations.

The topic of assessing the impact of a new noise source in the community has been covered extensively by the U.S. Environmental Protection Agency (EPA). Research sponsored by the EPA in the 70's provided the basis for the development of noise descriptors and criteria by other federal agencies including various modal administrations of the Department of Transportation. Among the key findings of EPA research is that the day night sound level (Ldn) is the only suitable noise descriptor for comparing the noise impact of a new noise source with that of other noise sources in the community. Some of the reasons for this result are discussed in this report.

It is important to differentiate between two different contexts in which noise descriptors are used; noise impact assessment and noise source definition. This report deals with the former, development of a way to describe the impact of maglev noise on the community. The metric introduced above, the Ldn, is the appropriate noise descriptor general enough to accommodate all kinds of noise sources, including those with various magnitudes, durations, and times of day. An example of the other context is the need for a descriptor of the noise associated with a single passby of the maglev vehicle. In that case, the descriptor must provide information on characteristics of a single noise source apart from the general noise environment, for example, noise level vs. speed. This comparison is often made in terms of the maximum A-weighted sound level, Lmax, during a passby. Lmax is used in describing the magnitude of noise from a single event and for comparing the effectiveness of various mitigation measures.

The background for considering environmental noise criteria for maglev is discussed in the next subsection.

1.2 Basis for Criteria

No directly applicable research on community reaction to maglev noise has been published to date, and none was performed under this contract. However, there is a general speculation that the rapid onset rates of noise associated with the proximity of fast-moving vehicles to residences could increase annoyance compared with other transportation vehicles. In fact, measured time history signatures of the TR 07 show fast rise times for nearby receivers. However, there is a lack of data for community reaction to intermittent noise events with brief, high level bursts of noise. The U.S. Air Force has been actively working to develop noise criteria for such cases, directly related to military training routes, based on extrapolations of best available data.[1] This study relies on the similarity of high speed maglev time histories and sound spectra with low-flying aircraft for which some data are available from military training routes. An underlying weakness of such a comparison may be the fundamental difference in the orientation of the vehicle with respect to the receiver; aircraft sound blankets an area from an overhead flight path, while maglev noise emanates from a linear source subject to ground effects near the earth surface. A further unknown in comparing maglev noise with aircraft noise is the psychological effect relating people's startle reaction from sudden noise events to fear of accidents*, whereas if the source is recognized as maglev, the public may be more confident that it is a vehicle constrained to a prescribed track.

Section 2 includes a description of the expected noise characteristics of a high speed maglev system and compares the time history plots from the TransRapid 07 with those of aircraft overflights. The onset rates (how fast the noise levels increase in time) of low-flying jet aircraft are found to be nearly the same as the high speed runs of TR 07, suggesting that corrections proposed for military training routes to account for startle may be applicable to maglev under certain conditions.

The proposed noise descriptor and criteria are described in Section 3. Ldn provides a reasonable basis for describing the cumulative effect of maglev passbys, but an adjustment to account for startle is needed. A set of criteria based on the contribution of maglev noise to the ambient Ldn is described. Section 4 includes an example of applying the criteria for estimating noise impact using the proposed criteria.

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* A low-flying aircraft may be perceived as an unusual event, signalling an impending disaster.

2. NOISE CHARACTERISTICS OF HIGH SPEED MAGLEV

People in the U.S. have not been exposed to noise from very fast moving surface transportation sources on a daily basis. Therefore, any criteria based on expected reaction will have to be drawn from the similarities of noise characteristics of maglev systems and aircraft for which criteria have been, or are being, established. Where similarities are demonstrated, the assumption is made that the community reactions will be the same. However, because no data are available directly applicable to people's reaction to noise from this new source, a conservative approach is taken in adopting criteria.

2.1 Expected Configuration

This section gives a brief overview of the kind of system envisioned for a future high speed maglev operation.

2.1.1 Guideway

For safety reasons, a new maglev transportation system is expected to be on exclusive guideway. Consequently, the running surface will be separated from the ground surface, typically 5 to 10 meters above grade. Since a typical two-story house is 8 meters high, this means that a maglev train can be thought of as operating along the top of roofs and sometimes at treetop height in suburban residential areas. The consequence of this configuration for noise propagation is that the first and second rows of houses abutting maglev rights-of-way will have direct line of sight to the noise source, but that homes beyond the second row may have the benefit of shielding. Such a configuration differs from the noise propagation path of an aircraft directly overhead which radiate downward to whole residential areas, or from highways and at-grade railroads where the noise propagation path closely follows the ground and is strongly affected by ground effects and terrain features.

2.1.2 Vehicle Consist and Headways

The ultimate configuration of the U.S. maglev system has not been established. During the current system concept studies various alternatives are being developed to carry 4000 to 12000 passengers per hour each way. The system could carry this many passengers with either long trains or short trains, with different headways. Some planners favor frequent two-car trains in order to provide maximum flexibility in service. These trains would be approximately 50 meters long and would operate at extremely short (60 second to 120

second) headways during peak periods. Other concepts include 8- and 10-car trains operating with greater headways.

2.1.3 Power and Speed

Maximum speeds are proposed to be very high, up to 500 km/hr between cities, although lower speeds may be utilized in urban areas. Propulsion would be electro-magnetic as is the levitation.

2.2 Passby Noise Signatures

The presence of a high speed maglev system in close proximity to homes may result in a new noise unlike any other existing sources of community noise. This section discusses the implications of these noise events on the potential for startle due to the sudden approach of a very loud event.

2.2.1 Time History Characteristics of a High Speed Maglev Passby

High speed maglev passbys are characterized by high noise levels and brief durations. Maximum noise levels at 25 meters from the guideway range from 77 dBA at 160 km/hr to 98 dBA at 435 km/hr for the TransRapid TR 07, as shown in Figure 1. Durations of the noise event depend on the length of the train and the distance of the receiver from the guideway, but for the two-car TR 07 at 435 km/hr shown in Figure 1, it takes only 3 seconds for the sound to rise and fall to 20 dB of the peak. Figure 1 also shows asymmetry in the time history which is characteristic of a fast-moving vehicle; the noise level rises faster than it falls. The onset rate** for the 435 km/hr signature is 21 dB per second, while the rate of decay is about 10 dB per second. This asymmetry is due to a number of effects related to the speed of the vehicle, including Doppler effect, convective augmentation and sound sourcedirectivity.

**Onset rate is the average rate of change of increasing sound pressure level during a single noise event.

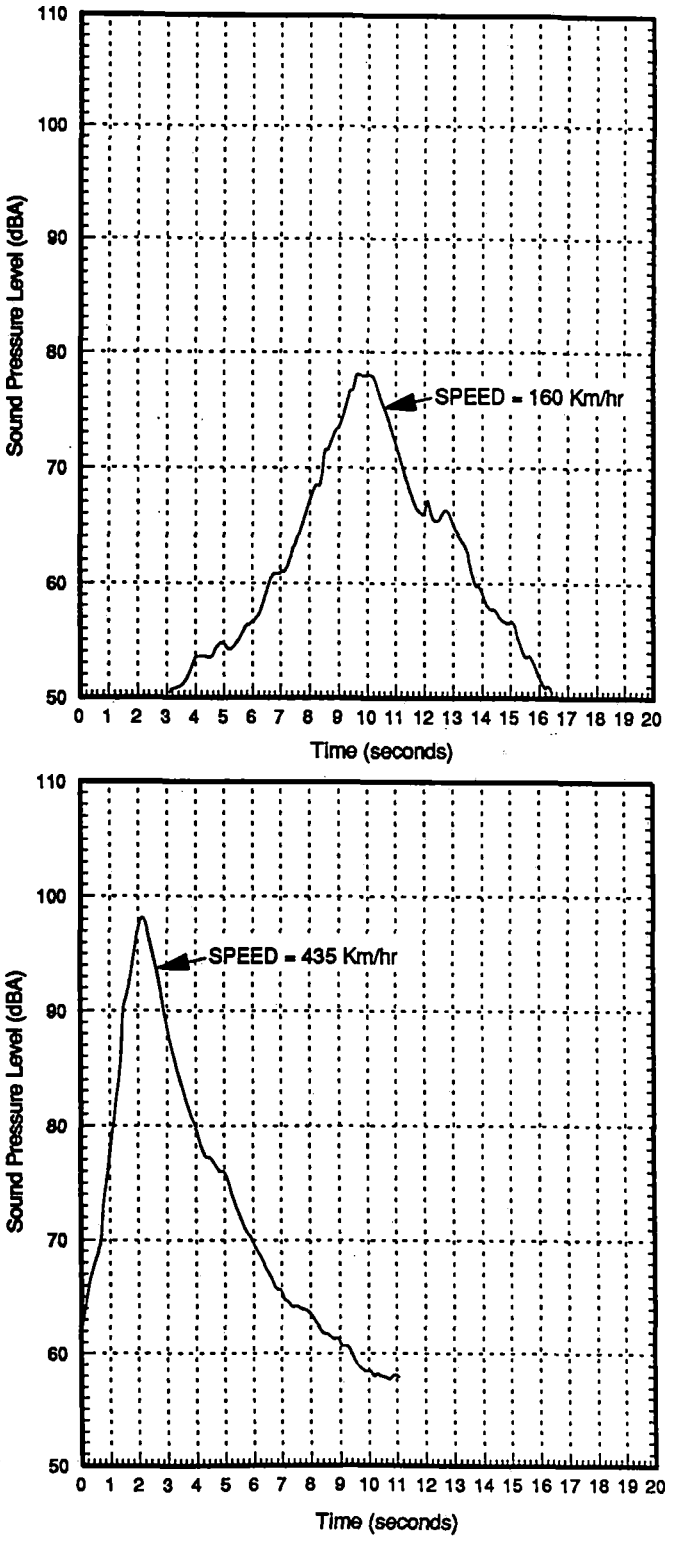

Figure 1. Time History of A-weighted Sound Levels of Maglev at 25 meters[2]

The onset rate is related to the rate of approach of a moving vehicle. More correctly, it is related to the rate at which the vector distance between the sound sources and the receiver is halved. Both speed and distance figure into the process. Measured onset rates for passbys of TR 07 measured by TUV Rheinland are shown plotted against the ratio of speed to distance in Figure 2. This plot shows how onset rate varies with the rate of change of angle between the train and the receiver. It can be seen that onset rate:

- changes directly as speed for a given distance,
- changes inversely as distance for a given speed.

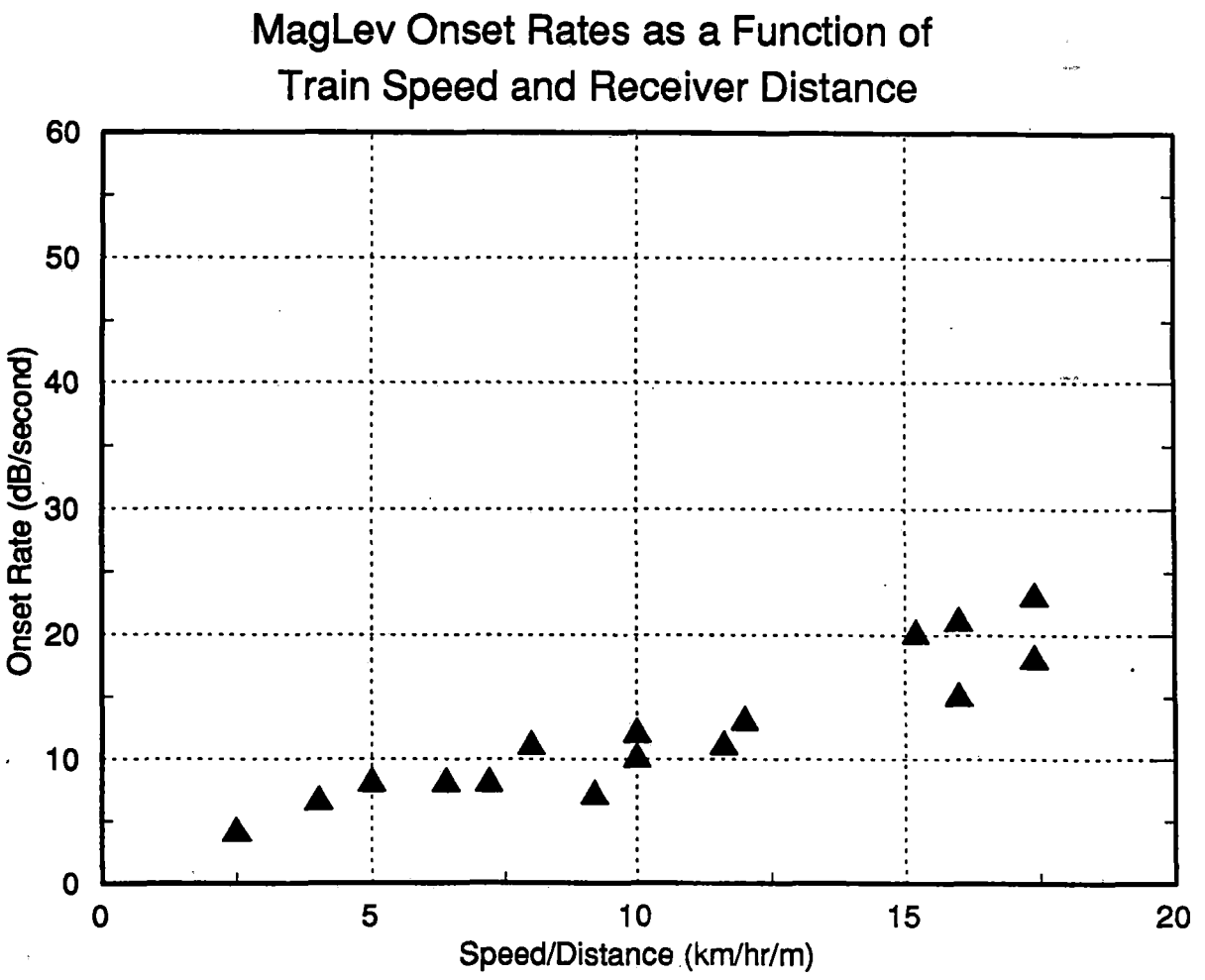

Figure 2. Measured Maglev (TR 07) Onset Rates as Function of Speed and Distance

The maglev time history signatures in Figure 1 are similar in shape to those shown in Reference 1 for individual flyovers of jet aircraft at low altitudes which are known to cause startle (Figure 3). For example, the onset rate of the low-flying B-1B shown in the figure is 15 dB per second and the B-52H is 10 dB per second for aircraft on military training routes. U.S. Air Force is considering special prediction metrics to take account of the increased annoyance response of communities due to startle.

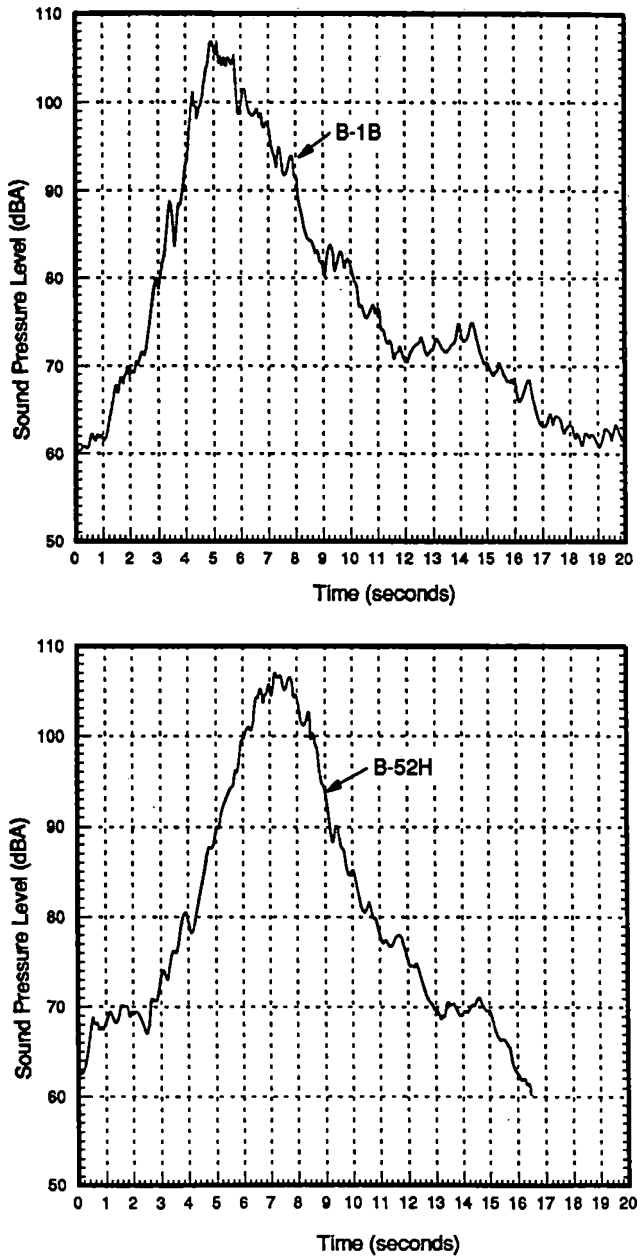

Figure 3. Time Histories of Low Altitude Aircraft Overflights (Ref. 1)

2.2.2 Annoyance Research Related to Onset Rate

Researchers report that sounds of approaching vehicles with signatures like these carry a sense of convergence and cause greater annoyance than receding sounds, perhaps from an increase in anxiety on the part of the receiver.[3] Moreover, sounds with fast rise time can be classified as impulsive in nature which are more annoying than noise with less rapid variations or steady noise with the same maximum noise level (see Ref. 1 for a summary). Various adjustments have been proposed to account for the increased impact of fast-rising sound events, but the bulk of evidence to date has focused on a 5 dB correction for "fast-rising" events. This means that for events with the same sound exposure level, people would judge an event with an abrupt change 5 dB noisier than one with a more gradual change even if the two sounds carry the same sound energy. Two such signals are shown in Figure 4; they both contain the same sound energy, but the second signal would be judged 5 dB noisier.

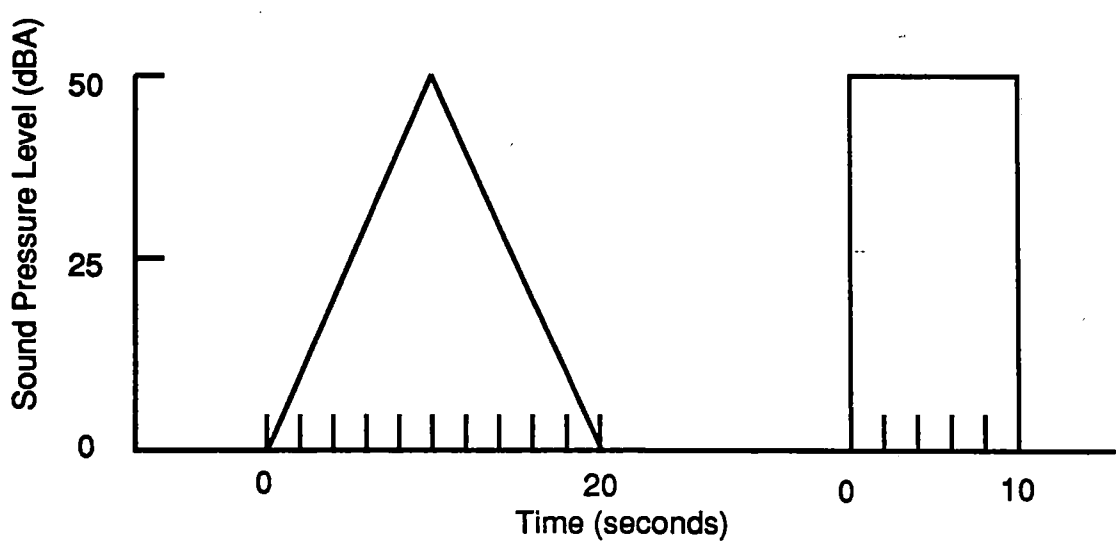

Figure 4. Single Events with Same Energy but with Different Onset Rates

These and other ongoing research findings have resulted in a proposed onset rate adjustment for assessing the potential noise impacts associated with military training routes by the U.S. Air Force. Although subject to revision and under current discussion,[4] the recommended adjustment to sound exposure level (SEL) of a single event is shown in Figure 5 (from Reference 1). The onset rate adjustment starts at 15 dB per second and reaches a maximum of 5 dB for onset rates greater than 30 dB per second. Between 15 dB per second and 30 dB per second, the adjustment follows the relation:

$$\text{Onset Rate Adjustment} = 16.6 \log_{10} (\text{onset rate}/15).$$

This adjustment is applied only to those single events where the maximum level exceeds the ambient level by 15 dBA, thereby eliminating from consideration events considered to have an insignificant effect.

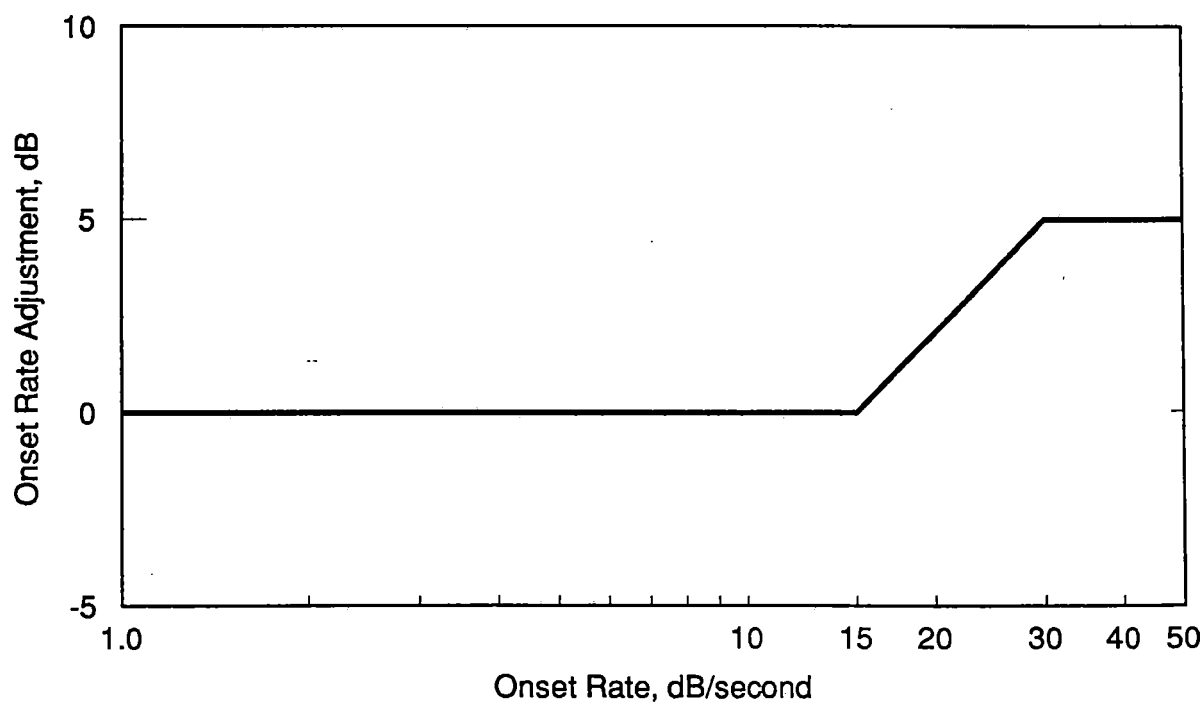

Figure 5. Proposed USAF Adjustment to SEL for Onset Rate

2.3 Noise Spectra

It has been demonstrated that sounds with rapid onset rates have about 5 dB more impact than those with gradual increases, and that high speed maglev noise signatures have rapid onset rates under some conditions. The next question has to do with judged noisiness of various frequency spectra, and to determine if high speed maglev is likely to have sound qualities judged to be more, or less annoying than other transportation sources.

2.3.1 Spectral Characteristics of a High Speed Maglev Passby

Noise from high speed maglev passbys is generally characterized by a broad band spectrum of frequencies over the sub-audible and audible range. In the first report of this series, the noise from high speed maglev trains is shown to be made up of many sources, including propulsion, mechanical/structural and aeroacoustic. Each type of source dominates a portion of the noise spectrum, but with a blending that makes it difficult to sort them out. A typical example is shown in Figure 6, where the lowest frequencies are associated with mechanical/structural radiation and the mid frequencies are associated with aeroacoustic sources. The spectra do not exhibit unusual characteristics, although pure tones can occur in maglev from mechanical sources (at the magnetic pole passing frequency) and from aerodynamic sources (periodic vortex shedding) (For example, see Figure 7).

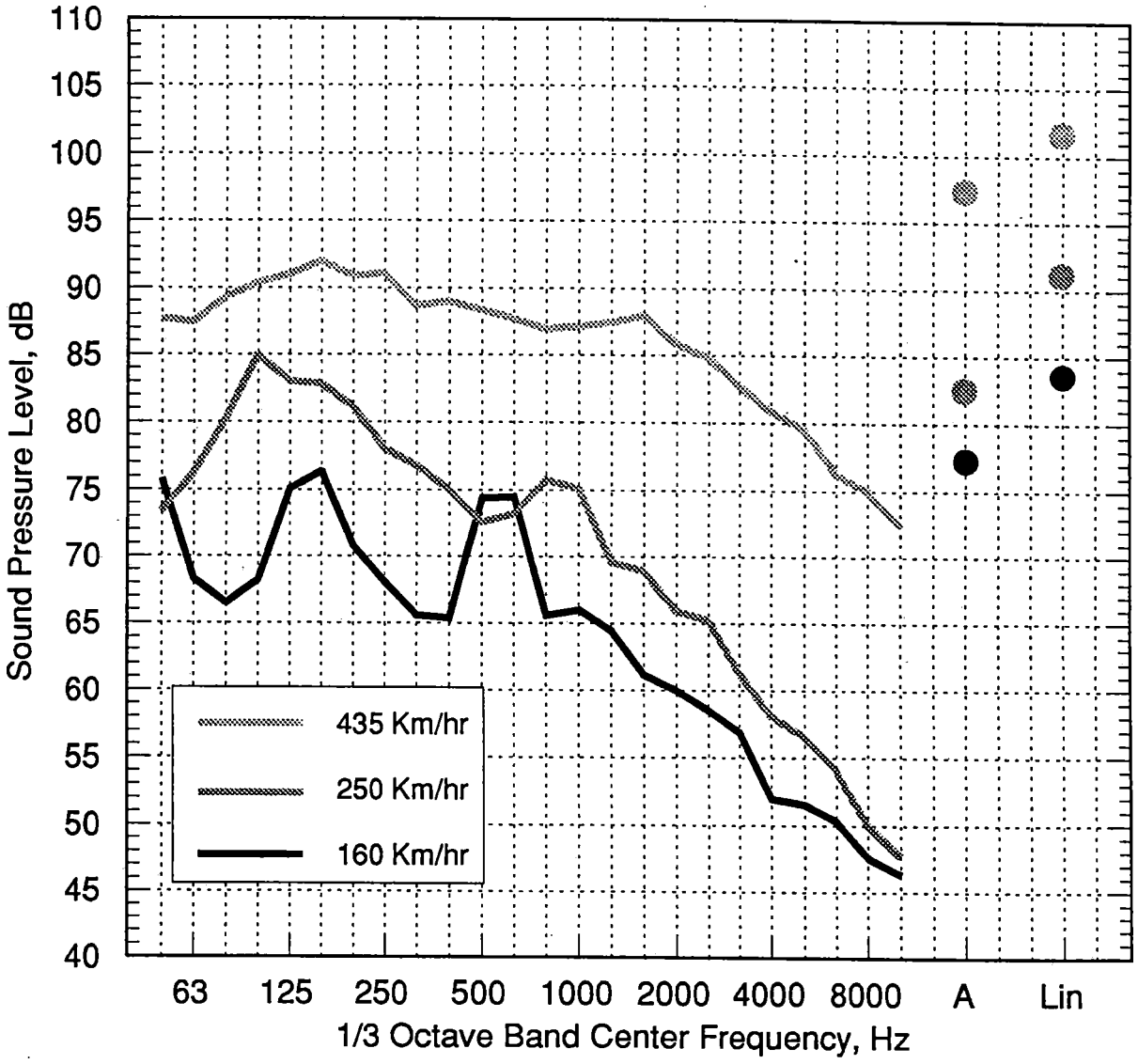

Figure 6. Noise Spectra of Maglev Passbys (Ref. 2)

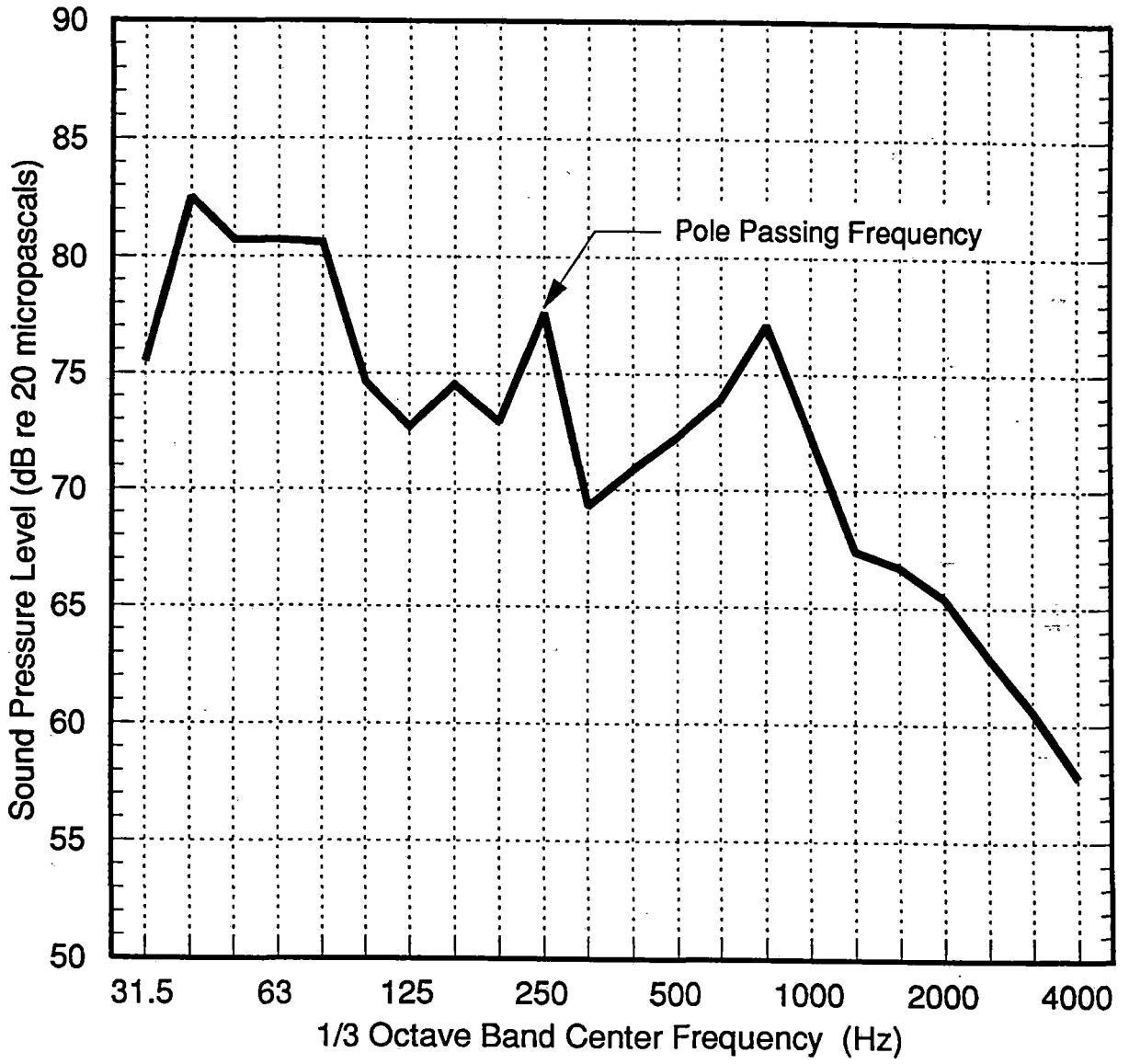

Figure 7. Spectrum of TR 07 at 68 m/s Showing Pure Tone (HMMH measurement)

2.3.2 Annoyance Research Related to Sound Spectra

Researchers have found that sounds with unusual frequency composition are judged to be noisier than those with broad-band sound characteristics, even when both sounds have the same measured sound exposure level. Noise with a pure tone content is an example of a particularly annoying sound, with a judged noisiness of 5 dB greater than sounds without a tone.[5] A great deal of effort has gone into in developing and testing noise descriptors incorporating tone corrections, especially for estimating annoyance from various types of aircraft. However, for a number of reasons, not the least of which is the availability of measurement instrumentation, the A-weighted sound level has evolved as the metric of choice for describing all types of environmental noise. Since no tone correction is incorporated in the A-weighting, any adjustment must be added to the sound level to account for the increased annoyance from tonal sounds. One example of such a correction is in the noise specifications for rapid transit vehicles; the American Public Transit Association Guidelines recommends a 3 dB penalty for presence of pure tones.[6] The position of the pure tone in the frequency spectrum may be important in the degree of increased annoyance; a very low frequency or a very high frequency tone may be less annoying than one located where human hearing is most sensitive. Consequently, when a penalty for pure tone is applied, frequency limits should be, but seldom are, imposed.

2.4 Cumulative Effects

The third factor that figures into people's reaction to noise is the duration of a single event and the cumulative duration of a number of separate events. Two questions are often asked: "Are people more annoyed by short noisy events or long quieter events?" and "Are people more annoyed by a long event, or by a series of shorter events with the same cumulative sound energy?" In relation to maglev, those questions concern the relative annoyance from long vs. short trains. For answers, psychoacoustical researchers point to laboratory data that indicate people judge equally noise events that have the same sound energy. This implies that loud, brief events are judged to be equivalent to longer, quieter events provided they have the same sound energy content. This is the basis for the equal-energy concept which underlies community noise response models. The concept is extended to multiple events by adding the energy of each event to develop a total. This simplification is especially attractive for computational purposes because the individual noise energies for different noise sources, or for different segments of time, can be easily combined to determine the total energy. Consequently, a new noise source can be compared to the existing ambient or to other sources using the same descriptor, and its contribution to the cumulative sound level can be easily determined.

Community response is related to the total noise energy in a specified time period. This finding, which is discussed in Section 3.1, is the basis for the acceptance of Leq and Ldn descriptors for community noise assessment. Leq is the single number "equivalent sound level," a steady noise level that contains the same acoustical energy as the actual time-varying noise pattern over the same time period. A major advantage of the equivalent sound level is the quality of being able to add Leq's from several different sources to determine a total Leq, provided the computation covers identical time periods, for example, one hour. The hourly Leq is a commonly-used descriptor for environmental noise; peak traffic hour Leq is used in highway noise computation models. For environmental noise descriptions it is understood that A-weighted sound levels are used for Leq.

Over the period of one hour, the Leq has been shown to correlate quite well with people's judgement of noise during that period. However, community response and public opinion surveys reveal that the same noise environment is considered more disturbing during the nighttime than during daytime. Lower nighttime noise levels are desirable for better sleep and relaxation conditions, but in addition, the ambient noise in most residential communities decreases by 10 dB or more at night. Consequently, any exterior noise source is likely to be more disturbing at night. To account for this increased potential for nighttime disturbance, the environmental noise descriptor, called the day-night sound level, Ldn, is used. Ldn is the Leq over a 24-hour period, but with a weighting factor of 10 dB applied to noises that occur during the nighttime hours of 10 p.m. to 7 a.m. Again, A-weighted sound level is assumed for the Ldn.

The cumulative effect of maglev noise on the environment, therefore, depends on the sound energy of each passby, the number of passbys, and the time of day of those passbys. For a description of the noise during peak hour of operations, the total Leq at a given location is the Leq of one operation at that location plus 10 times the logarithm of the number of operations in that hour:

$$Leq_{hour} = Leq_{passby} + 10 \log_{10} N \quad \text{dBA},$$

where Leq_{hour} is the total equivalent sound level in an hour,
Leq_{passby} is the contribution to the hourly Leq of one passby, and
N is the number of passbys with the same sound energy in the hour.

A more practical way of expressing the cumulative noise level during a period of time

involves the use of another time-integrated measure, the Sound Exposure Level (SEL). SEL is the total sound energy of one event normalized to a one-second time period, the fundamental time unit used in the MKS system. Determining the hourly Leq from a number of different sources is easy when the SEL of each source is known at a given location:

$$Leq_{hour} = \text{Energy Sum of all SEL's} - 10 \log_{10} 3{,}600$$

$$= \text{Energy Sum of all SEL's} - 35.6 \qquad \text{dBA,}$$

where Energy Sum means decibel addition of the SEL's,
and the 3,600 comes from the number of seconds in an hour.

One way of interpreting this expression is that the total sound energy is expressed in the first term, and the time period in seconds over which the sound energy is considered is expressed by the second term. This expression is used in computation methods because SEL's have been tabulated usually at a reference distance, such as 25 m, for various sources, such as automobiles, trucks, locomotives, train coaches, aircraft, etc., and the contribution of each can be added to determine the total energy in an hour.

SEL's from maglev operations can also be measured. For example, Figure 8 shows the SEL's measured on TR 07 normalized to a single vehicle of 25 m length. The original data came from TUV Rheinland's measurements of the 2-car TR 07 "train" with the rough assumption that sound energy is emitted equally from each car.*** The relationship between normalized SEL and speed, in Km/hr, is given by:

$$\text{Normalized SEL} = 79 + 40 \log (\text{speed}/200), \quad \text{dBA.}$$

The SEL at a reference distance for a train of maglev vehicles can be estimated from the following expression:

$$SEL_{train} = SEL_{car} + 10 \log_{10} N \qquad \text{dBA,}$$

where SEL_{car} = SEL of a single car at given speed at the reference distance of 25 m .

*** Not necessarily a valid assumption for all speeds; the leading car may actually radiate more aeroacoustic energy at high speeds than the trailer due to separation and reattachment of the boundary layer near the nose.

(Figure 8), and N = number of cars in the train.

The Leq for an hour of operations can be determined from the SEL, and the Ldn can then be determined using the expressions described previously. This is the building block used in the application example described in Section 4.

Note that although the SEL of each train depends on the length of the train, Ldn and Leq_{hour} are insensitive to the length of trains. It does not matter whether there are few long trains or many short trains carrying the passengers. All that counts is the number of cars passing a location during the given time period.

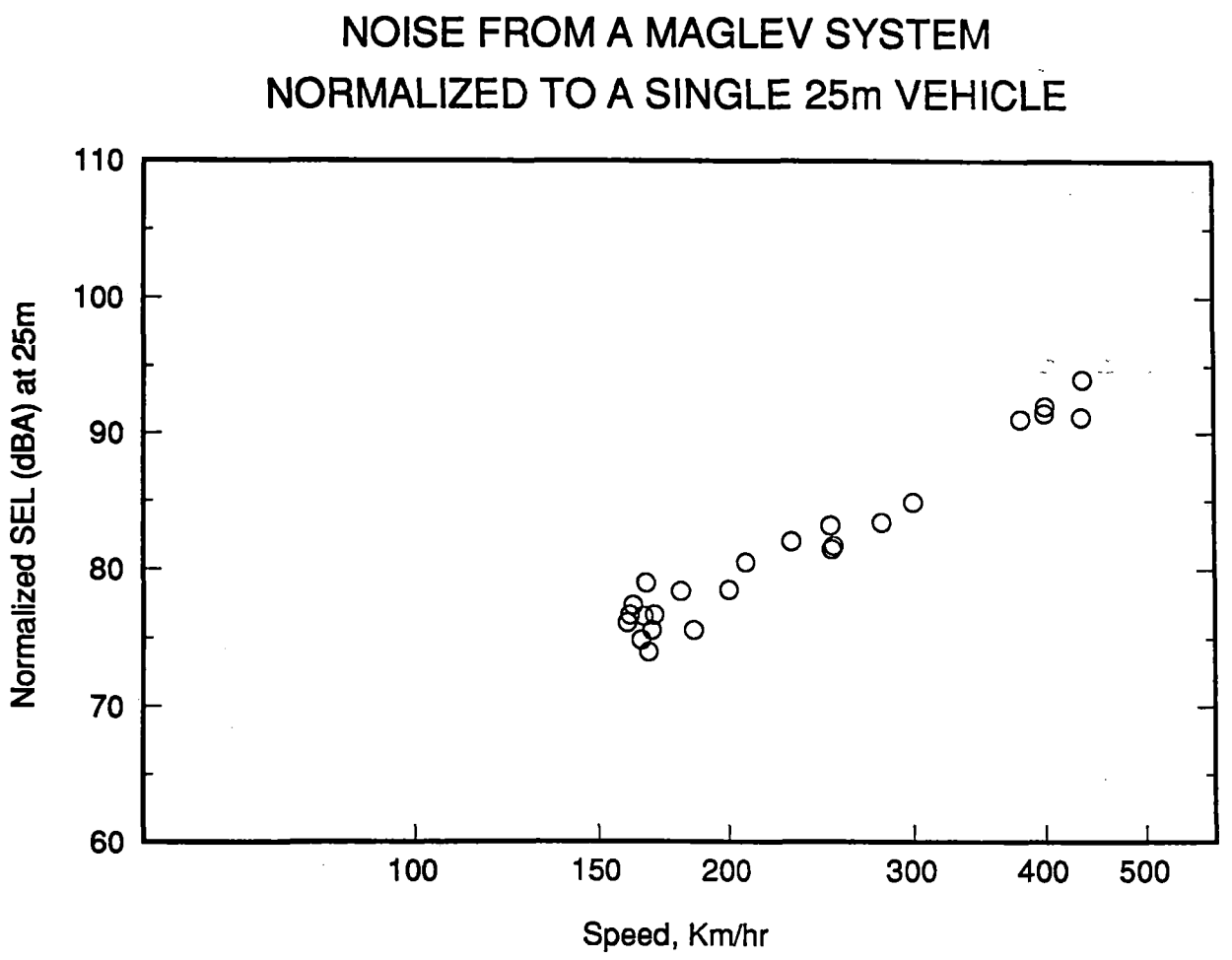

Figure 8. Normalized Sound Exposure Level of TR 07 at Distance of 25 m.

3. PROPOSED NOISE CRITERIA FOR HIGH SPEED MAGLEV SYSTEM

This section presents a proposed set of criteria to be used in evaluating noise impact from high speed maglev operations. These criteria are based on those included in the Federal Transit Administration's "Draft Guidance Manual for Transit Noise and Vibration Impact Assessment."[7] The criterion for the onset of Impact varies according to the ambient noise and predicted maglev noise levels and is determined by the threshold at which the percentage of people highly annoyed by maglev noise would start to become measurable. The corresponding criterion for Severe Impact similarly varies according to the ambient noise level as well as the maglev noise level, but is determined by a higher, more significant percentage of people highly annoyed by maglev noise. Background material on the development of the criteria from Reference 7 are summarized in this Section, and guidelines for the application of the criteria are included in Section 4.

3.1 Noise Descriptor

The noise descriptor adopted for use in the proposed criteria is the day-night sound level (Ldn). As described in Section 2, the Ldn is a measure of a receiver's cumulative noise exposure from all events over a full 24 hours, with all nighttime events given an extra weighting of 10 dB. Ldn is the metric of choice of most Federal agencies with noise standards (Department of Housing and Urban Development, Federal Aviation Administration, Environmental Protection Agency) and also has a wide acceptance internationally.

Ldn can be thought of as a unit in which complex environmental noise situations can be expressed in a single number. It includes:

- Spectral content corresponding to the way in which humans interpret sound, according to the A-weighting curve;
- Equal energy considerations in that the trade-off between sound level and duration corresponds to 3 dB per doubling of duration; and
- Time of day sensitivity in that nighttime events receive an extra weighting of 10 dB.

Furthermore, and perhaps most important, Ldn correlates well with the results of attitudinal surveys of residential noise impact. This conclusion resulted from a number of research and synthesis studies relating to community noise of all types supported by the U.S. Environmental Protection Agency (EPA) in the 1970's. In a large number of

community attitudinal surveys, transportation noise has been ranked among the most significant causes of community dissatisfaction. A synthesis of many such surveys on annoyance appears in Figure 9, where the percentage of people who are "highly annoyed" by their neighborhood noise is plotted against the Ldn of their neighborhoods.[8,9] The term "highly annoyed" is deliberately chosen; these are the people who in response to surveys placed annoyance from noise at or near the top of their neighborhood concerns. The dominating sources of noise in these surveys included aircraft, railroad, transit and street traffic. Based on the results of these data, Schultz proposed the universal transportation noise response curve relating percent highly annoyed to Ldn, as shown in the figure. It is assumed that the results of these surveys are source-independent, and that people would be highly annoyed by any transportation source that would cause noise at the corresponding levels. The equation for the least-squares fit to the annoyance data is:[10]

$$\%HA = 0.8553\ Ldn - 0.0401\ Ldn^2 + 0.00047\ Ldn^3.$$

Because it describes expected community annoyance to noise from transportation sources, this equation is used to develop the criteria curves in the next section.

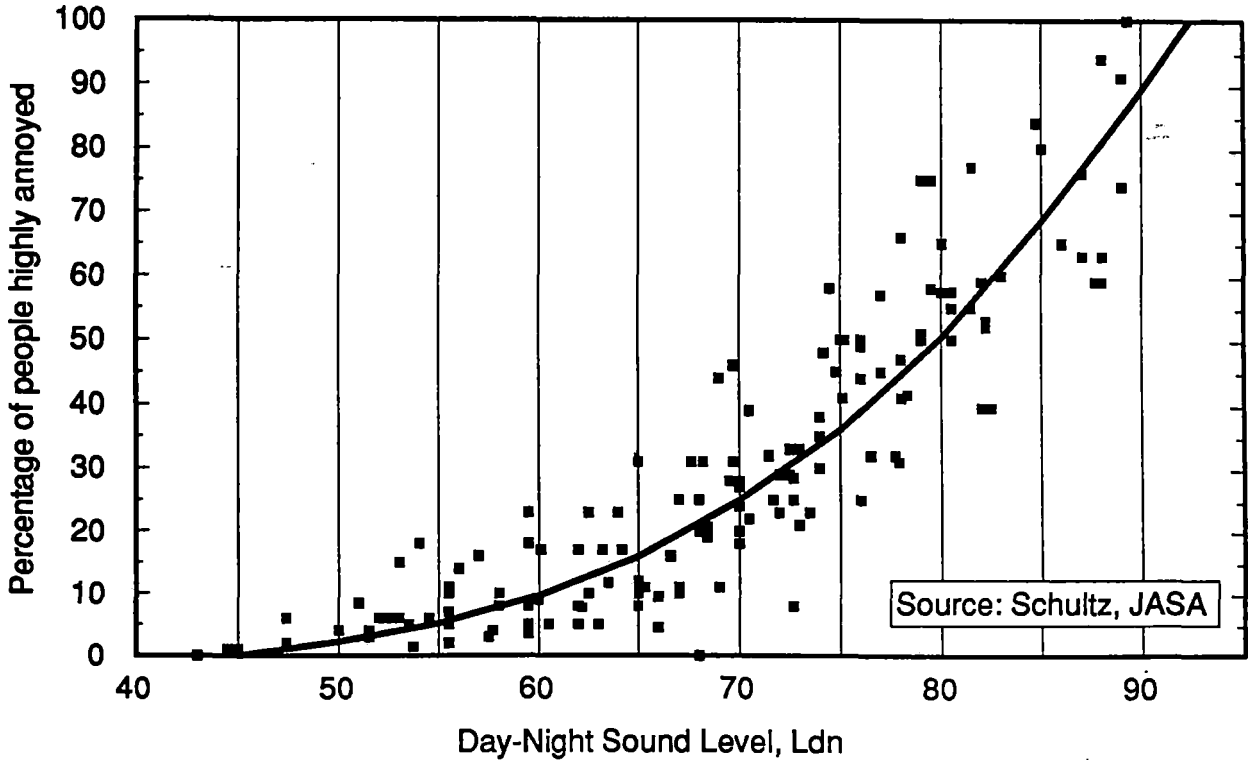

Figure 9. Community Annoyance Due to Noise

As discussed in Section 2, there is considerable evidence that an adjustment is required for sound signatures with rapid onset rates. Based on the foregoing discussion of Ldn and the need for an adjustment for onset rate, it is recommended that an "onset-rate adjusted day-night sound level" be used to assess noise impact from maglev operations. This unit is the Ldn contribution from maglev operations as computed from the SEL's of individual passbys, except that an adjustment is made to the SEL's for passbys with rapid onset rates. A simple adjustment is proposed for ease in application and for purposes of being conservative;

add 5 dB to the SEL for onset rates of 15 dB per second or more.

This adjustment for maglev differs from that of the USAF, where the adjustment gradually reaches 5 dB between onset rates from 15 dB/sec to 30 dB/sec.

Figure 10 shows the relationship of speed and distance to define locations where the onset rate exceeds 15 dB per second for a maglev train. This curve was determined using a "Single Vehicle Passby Program," developed by HMMH for the National Park Service.[11] This program accounts for divergence, directivity, convective augmentation, ground effect, atmospheric absorption and emission level (spectra) as a function of speed. TR 07 data measured by TUV Rheinland and HMMH were used to obtain the relationship shown in the figure.

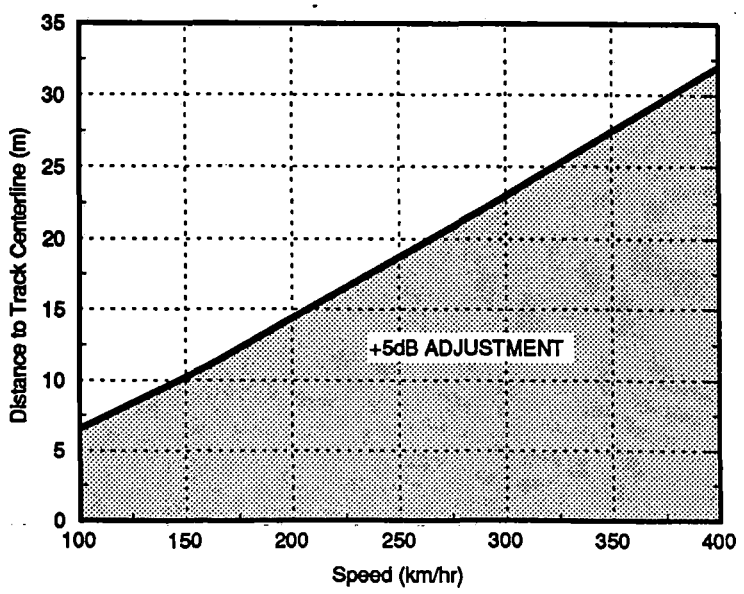

Figure 10. Proposed Onset Rate Adjustment to SEL's from Maglev

3.2 Noise Criteria

The noise impact criteria for maglev operations are shown graphically in Figure 11. These criteria are based on comparison of the existing noise levels and future noise levels of the maglev operations. These criteria are identical to those proposed by the Federal Transit Administration for assessing noise impact from urban transit operations (Reference 7), with the single difference that the "onset-rate adjusted Ldn" is used for maglev operations.

The noise criteria and descriptors depend on land use, designated either Category 1, Category 2 or Category 3:

> Category 1 includes tracts of land where quiet is an essential element in their intended purpose, such as nationally significant historic sites or outdoor concert pavilion.
>
> Category 2 includes residences and buildings where people sleep,
>
> Category 3 includes institutional land uses with primarily daytime and evening use such as schools, churches and active parks.

For Category 2 land use where nighttime sensitivity is a factor, the noise criteria use Ldn. For Category 1 and 3 land uses involving primarily daytime activities, the impact is evaluated in terms of the Leq for the noisiest hour of maglev-related activity during which human activities occur at a noise-sensitive location. The latter is referred to as "peak hour Leq." Because the Ldn and daytime peak-hour Leq have similar values for typical noise environments, they are used interchangeably to evaluate noise impact for Category 1 and Category 2 sites. However, because Category 3 sites are less sensitive, the criteria allow the maglev noise to be 5 decibels greater than for Category 1 and Category 2 sites.

The noise impact criteria are defined by two curves which allow increasing project noise levels as ambient noise increases up to a point, beyond which impact is determined based on maglev noise alone. Below the lower curve in Figure 11, a maglev system is considered to have no noise impact since, on the average, the introduction of the system will result in an insignificant increase in the number of people highly annoyed by the new noise. The curve defining the onset of noise impact stops increasing at 65 dB for Category 1 and 2 land use, a standard limit for an acceptable living environment defined by a number of Federal agencies. Maglev noise above the upper curve is considered to cause Severe Impact since a significant percentage of people would be highly annoyed by the new noise.

This curve flattens out at 75 dB for Category 1 and 2 land use, a level associated with an unacceptable living environment. As indicated by the right-hand scale on Figure 11, the project noise criteria are 5 decibels higher for Category 3 land use.

Between the two curves the proposed project is judged to have an impact, though not severe. The change in the cumulative noise level is noticeable to most people, but may not be sufficient to cause strong, adverse reactions from the community. In this transitional area, other project-specific factors must be considered to determine the magnitude of the impact and the need for mitigation, such as the predicted level of increase over existing noise levels and the types and numbers of noise-sensitive land uses affected.

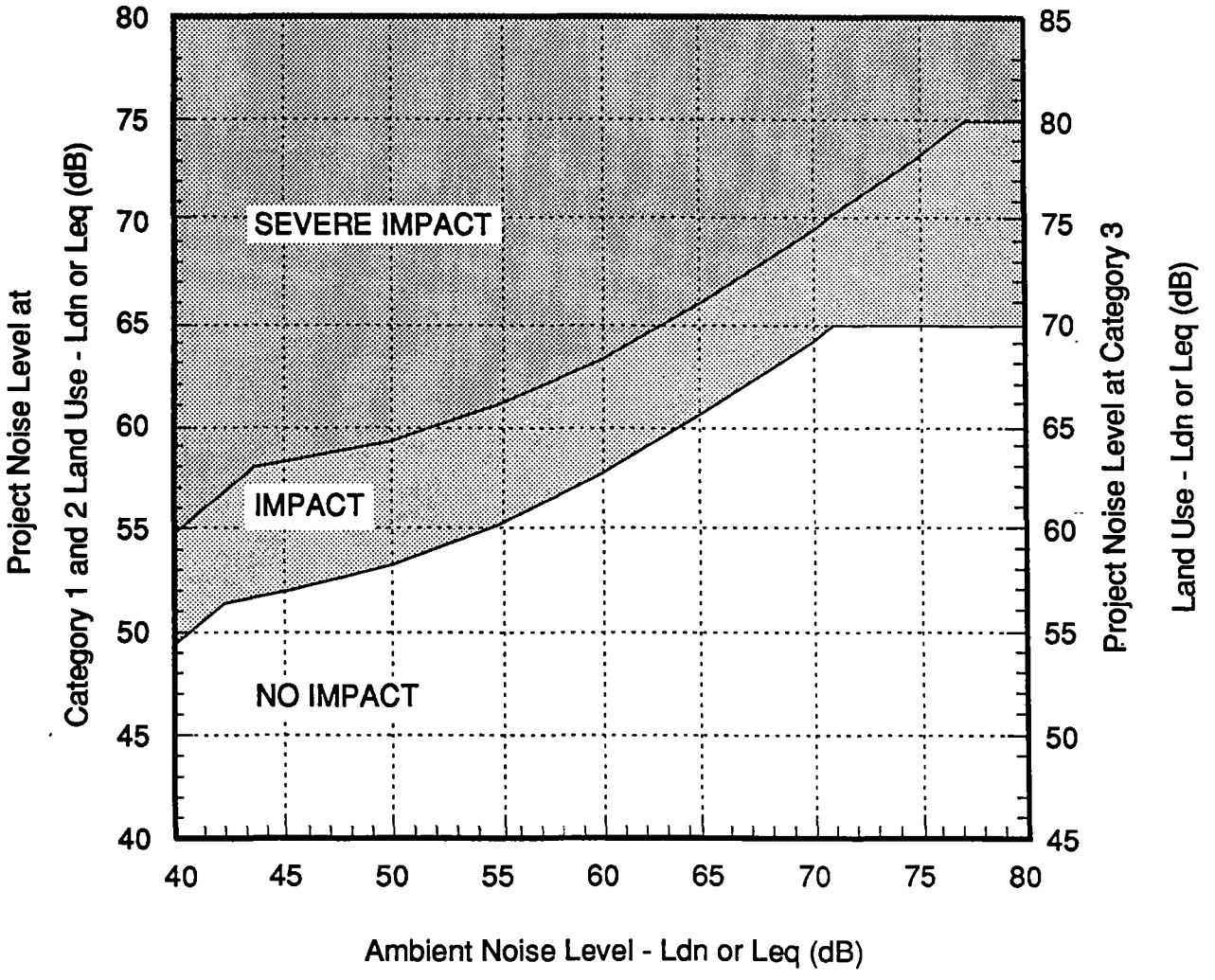

Figure 11. Proposed Noise Impact Criteria

3.3 BACKGROUND

The noise criteria have been developed based on well-documented criteria and research into human response to community noise. The primary goals in developing the noise criteria were to ensure that the impact limits be firmly founded in scientific studies, be realistically based on noise levels associated with new transit projects, and represent a reasonable balance between community benefit and project costs. This section provides a summary of the background information found more completely in Reference 7.

3.3.1 Basis for Noise Impact Criteria Curves

The lower curve in Figure 11 representing the onset of Impact is based on the following considerations:

- The EPA finding that a community noise level of Ldn less than or equal to 55 dBA is "requisite to protect public health and welfare with an adequate margin of safety."[12]

- The conclusion by EPA and others that a 5 dB increase in Ldn or Leq is the minimum required for a change in community reaction. (See Reference 12 for a full discussion.)

- The research finding that there are very few people highly annoyed when the Ldn is 50 dBA, and that an increase in Ldn from 50 dBA to 55 dBA results in an average of 2% more people highly annoyed (see Figure 9).

Consequently, the change in noise level from an existing 50 dBA to 55 dBA caused by a project is assumed to be a minimal impact. Expressed another way, this is considered to be the lowest threshold where impact starts to occur. Moreover, the 2% increment represents the minimum measurable change in community reaction. Thus the curve's hinge point is placed at a project noise level of 53 dBA and ambient of 50 dBA, the combination of which yields 55 dBA. The remainder of the lower curve in Figure 11 was determined from the annoyance curve (Figure 9) by allowing a fixed 2% increase in annoyance at other levels of existing ambient noise. As cumulative noise increases, it takes a smaller and smaller increment to attain the same 2% increase in highly annoyed people. For example, while it takes a 5 dB noise increase to cause a 2% increase in highly annoyed people at an

existing ambient noise level of 50 dB, an increase of only 1 dB causes the 2% increase of highly annoyed people at an existing ambient noise level of 70 dB.

The upper curve delineating the onset of Severe Impact was developed in a similar manner, except that it was based on a total noise level corresponding to a higher degree of impact. The Severe Noise Impact curve is based on the following considerations:

- The Department of Housing and Urban Development (HUD) in its environmental noise standards defines an Ldn of 65 as the onset of a normally unacceptable noise zone.[13] Moreover, the Federal Aviation Administration (FAA) considers that residential land uses are not compatible with noise environments where Ldn is greater than 65 dBA.[14]

- The common use of a 5 dBA increase in Ldn or Leq as the minimum required for a change in community reaction (Again, see Reference 12 for details).

- The research finding that the foregoing step represents a 6.5% increase in the number of people highly annoyed (see Figure 9).

Consequently, the increase in noise level from an existing 60 dBA to a cumulative level of 65 dBA caused by a maglev system represents a change from an acceptable noise environment to the threshold of an unacceptable noise environment. This is considered to be the level at which severe impact starts to occur. Moreover, the 6.5% increment represents the change in community reaction associated with severe impact. Thus the upper curve's hinge point is placed at a project noise level of 63 dBA and ambient of 60 dBA, the combination of which yields 65 dBA. The remainder of the upper curve in Figure 11 was determined from the annoyance curve (Figure 9) by fixing the 6.5% increase in annoyance at all ambient noise levels.

Both curves incorporate a maximum limit for the maglev noise in noise-sensitive areas. Independent of existing noise levels, Impact is considered to occur whenever the maglev Ldn exceeds 65 dBA and Severe Impact occurs whenever the maglev Ldn exceeds 75 dBA. These absolute limits are intended to restrict activity interference by maglev noise.

4. APPLICATION METHOD

4.1 Procedure for Noise Impact Assessment

The procedure for assessing impact is to determine the pre-project ambient noise level and the predicted maglev noise level at a given site, in terms of either Ldn or Leq as appropriate, and to plot these levels on Figure 11. The location of the plotted point in the three impact ranges is an indication of the severity of the impact.

The noise criteria are to be applied outside the building locations for residential land use and at the property line for parks and other significant outdoor use. However, for locations where land use activity is solely indoors, noise impact may be less significant if the outdoor-to-indoor reduction is greater than for typical buildings.

It is important to note that the criteria specify a comparison of future project noise with existing ambient noise and not with projections of future "no-build" noise levels (i.e. without the project). Furthermore, it should be emphasized that it is not necessary nor recommended that existing ambient noise levels be determined by measuring at every noise-sensitive location in the project area. Rather, the recommended approach is to characterize the noise environment for "clusters" of sites based on measurements at representative locations in the community. Guidelines for selecting representative receiver locations and determining ambient noise are provided in Reference 7.

The noise impact criteria are defined by the two curves delineating onset of Impact and Severe Impact. Below the lower curve in Figure 11, a proposed maglev system is considered to have no noise impact for any of the above land use categories. Maglev noise above the upper curve is considered to cause Severe Impact for all land use categories. Severe noise impacts are considered "significant" as this term is used in the National Environmental Policy Act (NEPA) and implementing regulations.

Between the two curves the proposed project is judged to have an impact, though not severe. In this range, other project-specific factors must be considered to determine the magnitude of the impact and the need for mitigation, such as the predicted level of increase over existing noise levels -- where the plotted points lie with respect to the upper curve -- and the types and numbers of noise-sensitive land uses affected. Whether the noise impact is determined "significant" in the context of NEPA will depend on these factors, as well as the ability to mitigate noise to more acceptable levels.

4.2 Example of Application of Criteria

For our example of noise impact from the introduction of maglev as it exists now without noise mitigation, we will look at the existing passenger train service provided in the Northeast Corridor between Boston and New York. The proposed criteria are based on Ldn which requires consideration of the noise from train passbys during daytime (7 am to 10 pm) and nighttime (10 pm to 7 am) hours separately. The example is based on a selected point along the route, a suburb of Boston. Residences in this area are located typically as close as 30 m from existing tracks. Urban or suburban residential areas with population density of 2,500 people per square kilometer are expected to have an existing ambient Ldn of 60 dBA (from Reference 12). With that number as the existing ambient, the proposed criteria show that Ldn's of 58 dBA and 63 dBA from a new source would cause "impact" and "severe impact," respectively (from Figure 11).

Current 1991 Northeast Corridor service between Boston and New York has a total of 16 day and 6 night trains passing through the suburbs of Boston. Assuming the same frequency and a similar level of service could be provided by 10 - car maglev trains with the same schedule, the normalized SEL from Figure 8 is converted to SEL for a 10-car train at a speed of 400 Km/hr using the SEL equation in Section 2.4, with the "onset rate adjustment" obtained for the appropriate speed from Figure 10. For a speed of 400 Km/hr, Figure 10 shows an addition of 5 dB for sites within 32 m of the guideway.

Ldn is subsequently obtained from spreading out the energy contained in 22 total events over 24 hours, but first adding 10 dB to each nighttime event (maglev passbys). The result is an Ldn of 71.5 dBA at 25 m. The line labeled "Boston suburb" in Figure 12 illustrates the distances from the guideway that would considered to be impacted using the proposed criteria. The noise propagation with distance over open terrain was taken from actual measurements at the TR 07 test track. The discontinuity in the Ldn line at 32 m occurs because that is the point at which the onset rate is expected to drop below 15 dB/sec (as shown in Figure 10). Impact would occur for any residence within 80 m of the guideway and severe impact would result for any residence within 40 m.

The method can be employed in reverse to determine the speed at which no impact will occur for a residential area. For example, if the nearest house was 30 m, the speed would have to be reduced to 267 Km/hr to fall into the "no impact" zone of Figure 11.

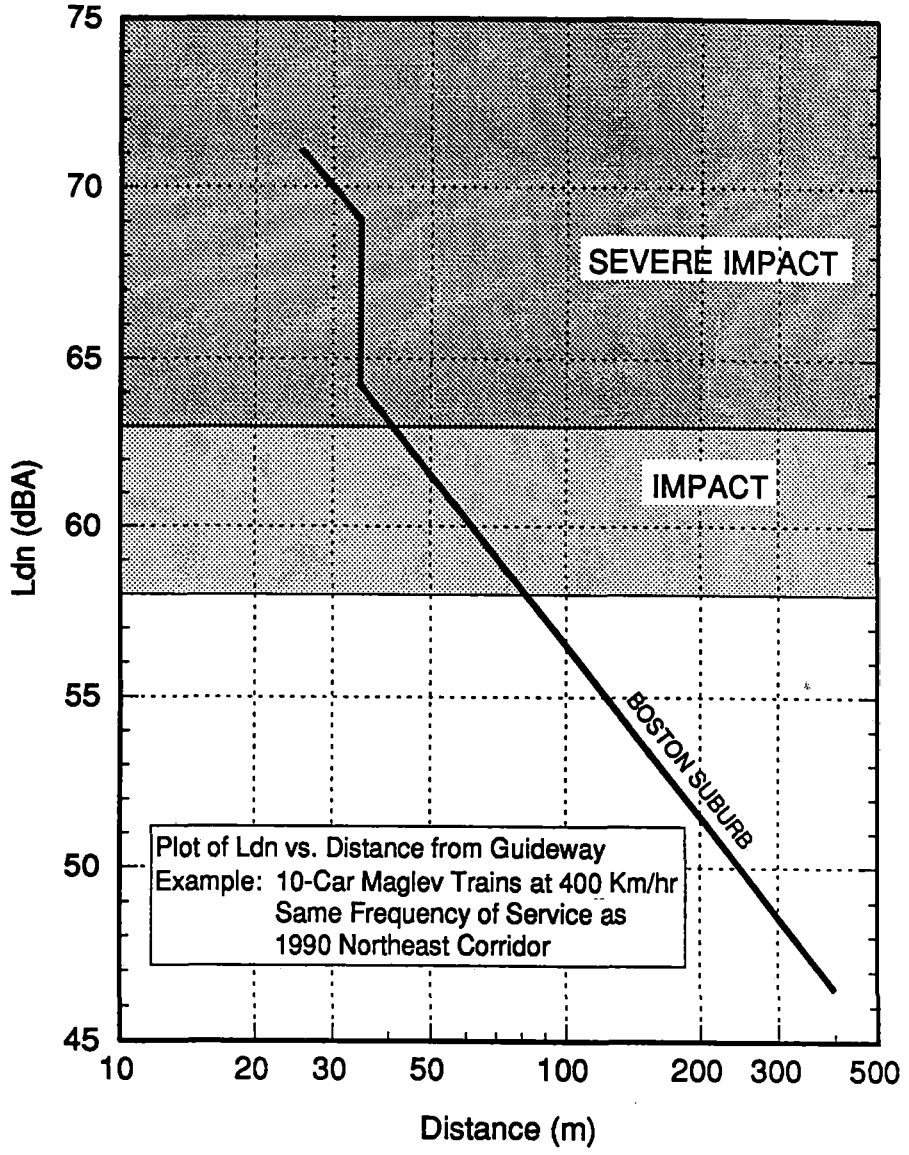

Figure 12. Ldn vs. Distance for Examples

5. REFERENCES

1. Plotkin, Kenneth J., L.C. Sutherland, J.A. Molino, "Environmental Noise Assessment for Military Aircraft Training Routes; Volume 2: Recommended Noise Metric." Wyle Laboratories Report WR 86-21 prepared for Wright-Patterson Air Force Base, AAMRL/BBE, April 1987. (NTIS No. AD-A181 278)

2. TUV Rheinland, Gerauschmessungen an der Magnetschnellbahn TR 07 und an anderen Verkehrssystemen im Vergleich (Noise Measurements of the Maglev TR 07 and Other Transportation Systems in Comparison), Institut fur Energietechnik und Umweltschutz, Bericht-Nr.: 933/329005/05-06, 4 July 1990.

3. Rosinger, G.,Nixon, D.W. and Von Gierke, H.E., "Quantification of the Noisiness of 'Approaching' and 'Receding' Sounds," J.Acoust.Soc.Am., 48, pp. 843-853, October 1970.

4. Private communication between R. Horonjeff of HMMH with Jerry Speakman, Armstrong Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio 45433.

5. Pearsons, Karl S. and Ricarda L. Bennett, "The Effects of Temporal and Spectral Combinations on the Judged Noisiness of Aircraft Sounds," Final Report FAA-NO-69-3, by Bolt, Beranek and Newman, Inc. for the Federal Aviation Administration, June 1969.

6. American Public Transit Association, "1981 Guidelines for Design of Rapid Transit Facilities," Section 2.7, Noise and Vibration, 1981.

7. U.S. Department of Transportation, Federal Transit Administration, "Guidance Manual for Transit Noise and Vibration Impact Assessment," Draft Report No. UMTA-DC-08-9091-90-1, July 1990.

8. Schultz, Theodore J., "Synthesis of Social Surveys on Noise Annoyance," Journ. Acoust. Soc. Am., Vol 63, No. 8, August 1978.

9. Fidell, S., Barber, D.S., and Schultz, T.J., "Updating a Dosage-Effect Relationship for the Prevalence of Annoyance Due to General Transportation Noise," Journ.Acoust. Soc. Am.,Vol 89, No. 1, January 1991.

10. Schultz, T.J. "Noise Rating Criteria for Elevated Rapid Transit Structures," U.S. Department of Transportation Report No. UMTA-MA-06-0099-79-3, May 1979.

11. Anderson, G.S., "Single Vehicle Passby Program," computer program developed for the National Park Service.

12. U.S. Environmental Protection Agency, "Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety," EPA report number 550/9-74-004, March 1974.

13. U.S. Department of Housing and Urban Development, "Environmental Criteria and Standards," 24 CFR Part 51, 12 July 1979; amended by 49 FR 880, 6 January 1984.

14. U.S. Department of Transportation, Federal Aviation Administration, "Federal Aviation Regulations Part 150: Airport Noise Compatibility Planning," January 1981.

SECTION 3

PRELIMINARY DESIGN GUIDELINES FOR NOISE CONTROL ON HIGH SPEED MAGLEV TRAINS

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

PREFACE

This report is the third of four reports to be prepared under U.S. Department of Transportation Contract # DTFR53-91-C-00074, "Noise from High Speed Magnetically Levitated Transportation Systems." The reports under this contract cover the following areas:

1. Characterization of Noise Sources
2. Noise Criteria for High Speed Maglev Systems
3. Design Guidelines based on Noise Considerations
4. Recommendations for Acoustic Test Facility for Maglev Research.

It presents information for use by planners and engineers for the design and implementation of high speed maglev systems in the United States. Although much of the information should be considered preliminary, it can be used to develop a first level estimate of the noise impacts and mitigation measures for a maglev system.

INTRODUCTION AND EXECUTIVE SUMMARY

This report builds on the first two reports of this series and provides preliminary guidelines on the prediction, assessment and mitigation of noise from maglev systems. The first report identifies noise sources from high speed maglev operations and recommends further research to help determine the unknowns. The second report reviews existing criteria and proposes noise criteria tailored to the expected community reaction to a new noise source with the characteristics of high speed maglev. This third report provides noise and vibration guidelines for assessment and design for this new technology. Because the technology has only recently been developed, research on maglev noise source mechanisms is in its infancy. Plans are being made for the introduction of demonstration systems, but how these systems will fit into the existing transportation network of the United States is largely unknown. If such a system is to be used at its full potential it will serve city pairs with fast and frequent service from convenient terminals near population centers. Siting a new transportation corridor may be very difficult given environmental and cost constraints. Mature or unused existing transportation corridors are therefore being considered for alignments of maglev systems. These corridors typically pass through suburban and urban areas in close proximity to residential buildings and other noise sensitive sites. Consequently, mitigation of adverse noise effects must be taken into consideration at the outset, and mitigation measures should be designed into the new systems. Research on maglev is still in its early stages and just as in its other developmental areas, noise control will be a part of the design and development process. This report provides information on the likely noise effects of the introduction of a new maglev system and provides preliminary guidelines for the application of noise control treatments.

The report has two parts, Environmental Guidelines and Design Guidelines. Under Environmental Guidelines, we provide a framework for assessing maglev environmental noise issues, discussing noise descriptors, criteria, procedures for prediction and assessment of the noise from a new maglev system. The second part, Design Guidelines, reviews the various known noise source mechanisms associated with the vehicle and the guideway and suggests ways in which these noise sources can be controlled.

1. ENVIRONMENTAL GUIDELINES

1.1 Noise Descriptors

The sounds that we hear are the result of very small pressure fluctuations in the atmosphere around us. In order to describe the signal content of these pressure fluctuations, acousticians have developed methods of analysis that differentiate among loudness, pitch and time history of sound. This sub-section is intended as a brief introduction to the descriptors to be used in this report. More detail can be found in an acoustical text or noise control handbook. Although some authors take care to define them separately, throughout this report we use the terms "sound" and "noise" interchangeably.

1.1.1 Noise Level, Decibels

Sound is a description of pressure oscillations above and below the mean atmospheric pressure. The amplitude of oscillation is related to the energy carried in a sound wave; the greater the amplitude, the greater the energy, and the louder the sound. The mean value of the pressure oscillations is always the atmospheric pressure; consequently, to describe an effective value of sound pressure, we use the root mean square pressure. The full range of sound pressures encountered in the world is so great that it becomes more convenient to compress the range by the use of the logarithmic scale, resulting in one of the fundamental descriptors in acoustics, the **sound pressure level, (L_p)**, defined as:

$$L_p = 20 \log_{10} (p/p_{ref}), \text{ in decibels (dB), where}$$

p is the sound pressure and p_{ref} is the reference sound pressure, internationally adopted to be 20 micropascals. In this report, the term **noise level** also refers to the sound pressure level, L_p.

1.1.2 Frequency Spectrum, A-Weighting

In Section 1.1.1 we relate noise level to the amplitude of pressure oscillations. Another aspect of the oscillation is its **frequency**, the number of complete cycles above and below the mean value that occurs in a unit time. The unit is cycles per second, called Hertz (Hz). When a sound

is analyzed, its energy content at individual frequencies is displayed over the range of frequencies of interest, usually the range of human audibility from 20 Hz to 20,000 Hz. This display is called a **frequency spectrum**. Three types of spectra are commonly used in acoustics: narrow band, where the sound energy is divided into equal frequency units of constant bandwidth, e.g. one Hertz or five Hertz bands; octave band, and one-third octave band, where the sound energy is divided among constant percentage bandwidths of 70% and 23% of the center frequency, respectively. One-third octave band spectra are generally used as a diagnostic tool for differentiating among sound sources because they are narrow enough to provide detailed information about the frequency content of a wideband noise signal, yet not too narrow to be overly sensitive to frequency shifts by Doppler effects of moving sources.

Sound is measured using a sound level meter, with a microphone that is designed to respond accurately to all audible frequencies. On the other hand, the human hearing system does not respond equally to all frequencies. Low frequency sounds below about 400 Hz are progressively and severely attenuated, as are high frequencies above 10,000 Hz. To approximate the way the human interprets sounds, a filter circuit with the same frequency characteristics as the typical human hearing mechanism is built into sound level meters. Measurements with this filter enacted are referred to as **A - Weighted Sound Pressure Levels**, expressed in dBA. Sounds at frequencies below 20 Hz (infrasound) and above 20,000 Hz (ultrasound) are generally imperceptible by the human hearing system and are consequently neglected in an environmental analysis.

1.1.3 Noise Descriptors: Lmax, Leq, SEL and Ldn

Another characteristic of sound in the environment is its fluctuation in level over time. Several descriptors have been developed to provide single number metrics for these variations. The time history of a typical maglev passby is shown in Figure 1. As the vehicle approaches, passes by, and recedes into the distance, the sound pressure levels rise and fall accordingly. Although detectable at levels slightly lower than the background sound level, the passby event is considered to occur over a duration containing most of the sound energy, such as within 10 dBA or 20 dBA of the peak. Note that although it looks like a great deal of the passby sound energy lies below the background level, the vertical scale is actually a logarithmic quantity, so each 10 dB increase represents 10 times more sound energy.

The descriptor used for representing the highest sound level of a single event, such as the passby of a maglev vehicle in Figure 1, is the **Maximum Level (Lmax)**. Lmax in dBA is commonly used to compare noise levels from different vehicle passbys, but it is important to understand that unless the sound is steady and continuous, the maximum level occurs for only a short time during an event. It is usually dominated by the single loudest source, which may be only one vehicle in a long train. A shortcoming of Lmax is that it ignores the duration of the event, an important environmental consideration. A single event descriptor that accounts for both level and duration of a sound is the **Sound Exposure Level (SEL)**, which is a single number unit in decibels that describes all the sound energy received at a given point from an event like that depicted in Figure 1, but normalized to a one-second duration. Technically, the duration of the entire event must be included in the normalization; however, in practice a duration like that shown in Figure 1 as "measured duration" is used because it is difficult to measure noise from portions of events below the background level. The normalization to one second allows comparison of the sound energy, and eventual combination, of different types of events on a common basis. For example, the SEL can be used to compare the sound energies emitted by various kinds of trains, even if they have different lengths.

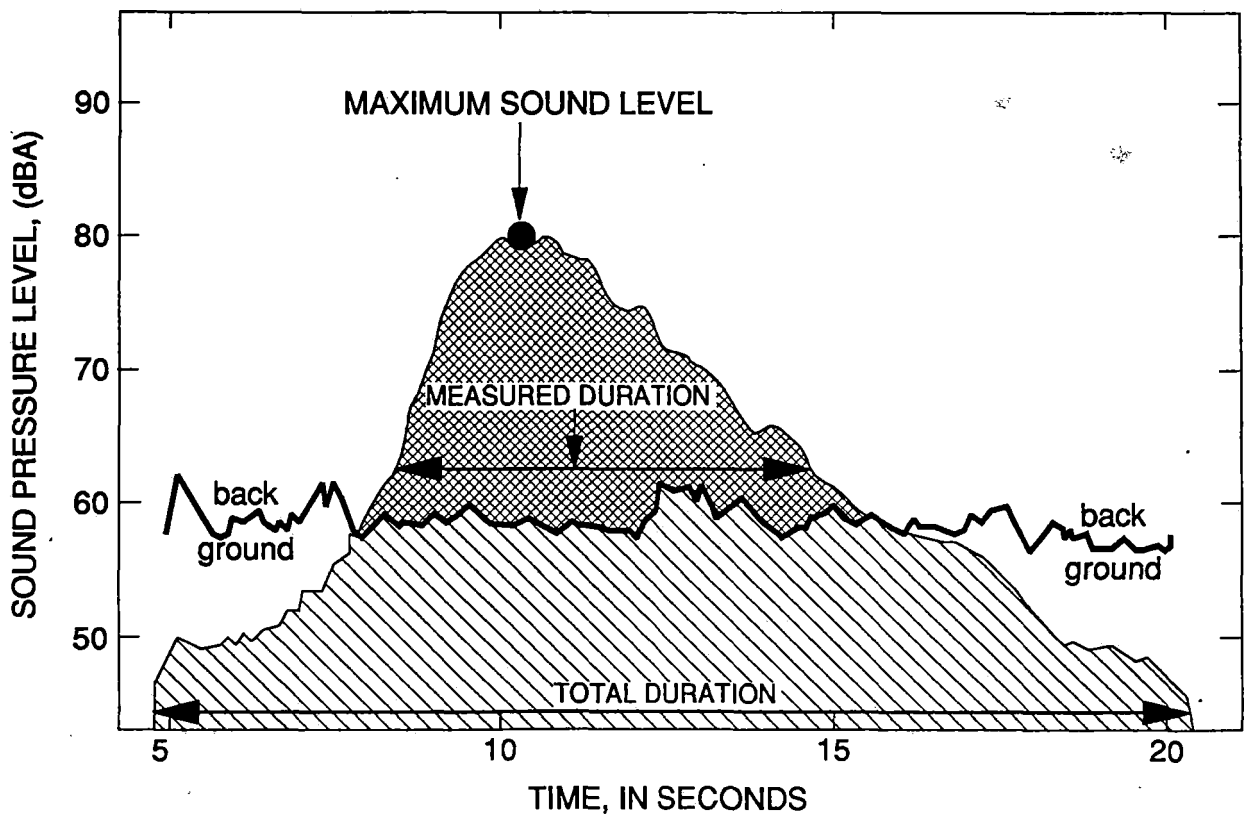

Figure 1. Typical Noise Time History of a Vehicle Passby

The descriptor used for cumulative noise exposure in the environment is the **Equivalent Sound Level (Leq)**. This is the level of a steady sound which, over a referenced duration and location, has the same A-weighted sound energy as the fluctuating sound. The duration of one hour is commonly used in environmental assessments. Researchers in Germany often describe train noise by the "passby level" which is the Leq over the time it takes for the train to pass. The "passby level" is typically somewhat lower than the actual Lmax because it is less influenced by a single dominant source. Environmental impact assessments in the United States use the **Day-Night Sound Level (Ldn)**. Ldn is a 24-hour Leq, but with a 10 dB penalty assessed to noise events occurring at night during the hours of 10 pm to 7 am. Ldn has been found to correlate well with the results of attitudinal surveys of residential noise from transportation sources. It is a good descriptor for the long-term noise environment, more like a noise "climate" of any area. Many Federal agencies use Ldn including Department of Housing and Urban Development (HUD), Federal Aviation Administration (FAA), Federal Transit Administration (FTA) and Environmental Protection Agency (EPA).

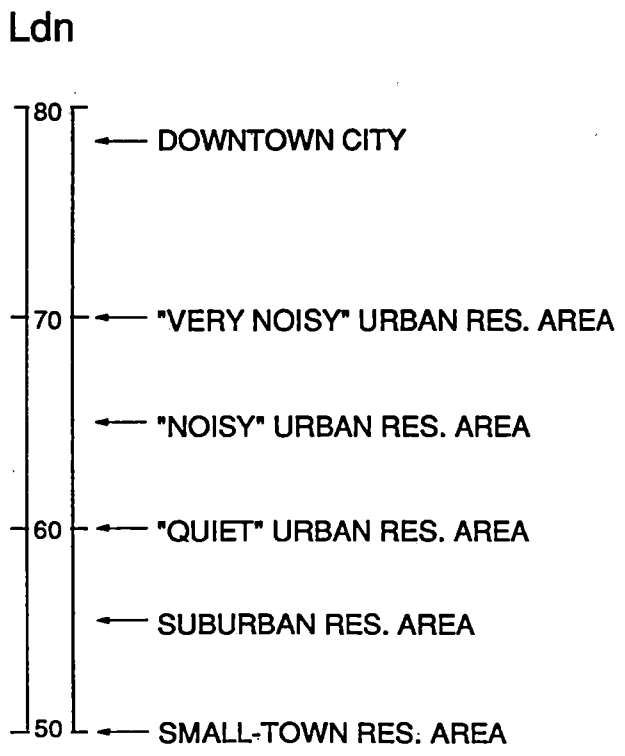

Figure 2. Typical Community Noise Levels, L_{dn}

1.2 Procedures for Noise Assessment

The procedure for assessing noise impact from a maglev system is shown in Figure 5 as adopted from the Federal Transit Administration's "Guidance Manual for Transit Noise and Vibration Impact Assessment."[1] The steps in the process are:

- predict the noise level in terms of SEL at the reference location of 25 meters,
- calculate the L_{dn} and Peak Hour L_{eq} at the reference distance taking account of the operational characteristics of the system,
- project the noise levels out to other distances using a sound propagation model,
- determine the ambient noise level of the proposed transportation corridor,
- assess the noise impact using criteria for maglev noise and identify impacted locations.

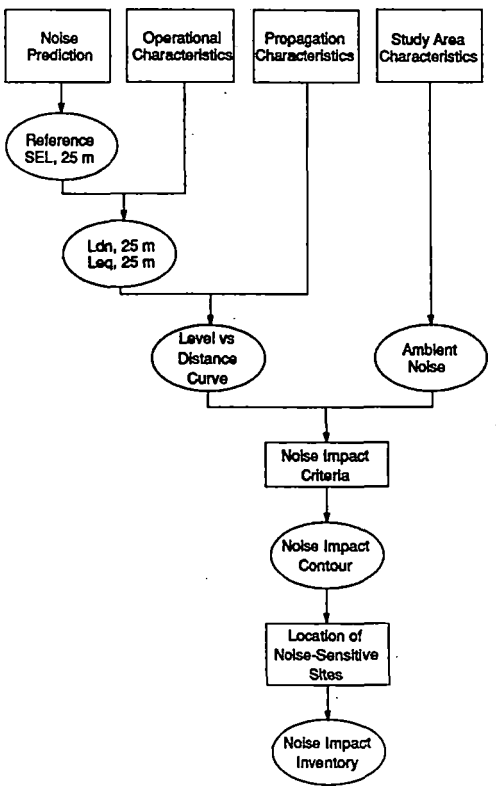

Figure 3. Procedure for Maglev Noise Assessment

1.3 Maglev Noise Prediction Method

This section provides a method for estimating the noise from a maglev system undergoing an environmental assessment according to the procedure outlined in Section 1.2.

Noise from high speed maglev trains is generated from many sources, all of which combine to produce the overall noise experienced at the wayside. It is important to realize that many noise sources continue to be present at all speeds, but some do not affect the noise of the vehicle passby at a particular speed. The noise generated by most sources is speed-dependent. Some sources which are dominant at low speed are in turn dominated by other sources at high speed. Consequently, a system noise prediction method will focus on the dominant source for each speed range. The procedure outlined requires determining the SEL for a single maglev train based on the known characteristics of the design. Then the cumulative effects of many passbys are added to determine the L_{eq} and L_{dn} for use in the environmental assessment. For purposes of additional information, L_{max} is also determined in the prediction procedures.

The steps in the maglev noise prediction method are as follows:

1. Compare maglev system design features with dominant noise sources in each speed range listed in following subsections.

2. Calculate Reference SEL for single vehicle for each speed range according to equations given in following subsections.

3. Calculate Reference SEL for train of N vehicles for each speed range.

4. Calculate Reference L_{eq} for each hour based on number of trains per hour both directions.

5. Calculate Reference L_{dn} based on daily train schedule.

6. Calculate L_{dn} at specific noise-sensitive receivers or determine noise contours by adjustments for distance and propagation conditions.

The noise predictions for the vehicle are based on the dominant sources for each speed range. The reference conditions are established as a reference distance of 25 meters from the centerline of each guideway or vehicle, with no mitigation or shielding of the vehicle from line of sight. For cases where the guideway has an effective sound barrier, the noise reduction is built into the guideway factor. The dominant noise sources are summarized below.

1.3.1 Vehicle Noise

Low Speed Range, 0 to 150 Km/hr (0 to 42 m/s)

Mechanical noise from the vehicle dominates maglev system noise primarily at speeds up to 100 Km/hr (28 m/s). With the vehicle at rest, noise is generated from auxiliary systems and equipment cooling fans. As the vehicle begins to move, other noise sources begin to come into prominence. A tonal hum from the electronics in the propulsion system grows in intensity as speed increases. Another tonal sound from the vehicle passing the magnetic poles and slots becomes evident as the vehicle speeds up, but this noise occurs at a very much lower frequency than electronic hum and does not influence the A-weighted sound level until higher speeds are reached. An electrodynamic maglev system (EDS) may require wheels for support at speeds up to approximately 100 Km/hr (28 m/s). Wheel/guideway interaction becomes the dominant noise source for these vehicles in the speed range over which they are deployed. Some electromagnetic maglev systems (EMS) can levitate at zero speed, and therefore do not require wheels. Consequently, the dominant noise factors from vehicle structure are fans and auxiliary equipment at rest, fans and wheels for EDS system at speeds up to 100 Km/hr (28 m/s), and fans and possibly propulsion system hum and pole passing noise for EMS over the same range. Each source is discussed below; their noise vs. speed relationships are shown in Figure 4.

FANS The size, number, location and type of fans are the important factors for estimating the noise of the cooling and auxiliary systems of a maglev vehicle. All of these factors are specific to a particular vehicle design. In general, an air-conditioned public light rail transit car 25 meters long with a capacity of 160 passengers generates a steady noise level of 63 dBA at 25 meters at rest with all auxiliaries operating. For these preliminary guidelines, our assumption is that without special mitigation, the noise of a single maglev vehicle at rest will be dominated by fans

at the steady level similar to a transit car. Consequently, we will assume for a single maglev vehicle at rest:

L_{max} (fans) = 63 dBA at 25 meters, and

Reference SEL (fans) = 81 + 10 $\log_{10}$ (t/60) , dBA, at Speed = 0 ,

Reference SEL (fans) = 65 - 10 $\log_{10}$ (s/28) , dBA, at Speed > 0,

where: t = dwell time in seconds for a vehicle at rest in a station,
s = speed in meters/second.

PROPULSION SYSTEM Two noise sources are associated with the propulsion system, electronic components of the control system and magnet pole passing, but neither are dominant at low speeds. The electronics in the control system for the propulsion system have a tonal noise, often characterized as a hum, which can be noticeable at the wayside at low speeds. (Inside the vehicle, this source is quite noticeable.) Fan noise dominates the A-weighted sound level from the propulsion system despite the distinct tonal character of the control system. Consequently, electronic hum will be neglected for predictions of exterior A-weighted sound.

Tonal noise from magnetic pole passing occurs with a characteristic frequency related to the speed divided by the pole pitch. At speeds above 150 Km/hr (42 m/s) this source can be significant, but at low speed the frequency is in a range heavily discriminated against by the A-weighting curve. Consequently, at low speeds we will assume:

Reference SEL (propulsion) = 0 dBA, at Speeds < 150 Km/hr (42 m/s) .

WHEELS Some maglev systems require wheels for vertical support and lateral guidance while the vehicle is stopped and at speeds too low for levitation. The speed at which landing gear and lateral guidance wheels can be retracted varies from system to system, but 90 Km/hr (25 m/s) is a typical speed for which full magnetic levitation can be assumed. The wheels are likely to be pneumatic rubber tires, similar to those used on aircraft. Noise from rolling tires on road surfaces has been researched by the U.S. Department of Transportation. Federal Highway

Administration's standard relation for noise emission level of automobiles as used in the authorized FHWA Highway Noise Computer Program (STAMINA) is applicable to a maglev system with wheels.[2] The following relationships give noise vs speed for a single maglev vehicle during the time it is running on its wheels.

$$\mathbf{L_{max}\ (wheels) = 69 + 38\ \log_{10}\ (s/28) + 10\ \log_{10}\ (N/4)}\ \ \mathbf{dBA\ at\ 25\ meters},\ \text{and}$$

$$\mathbf{SEL_{ref}\ (wheels) = 71 + 28\ \log_{10}\ (s/28) + 10\ \log_{10}\ (N/4)},\ \ \text{dBA, at Speed} > 0$$

where: N = number of tires contacting the guideway surface, and
s = speed in meters/second.

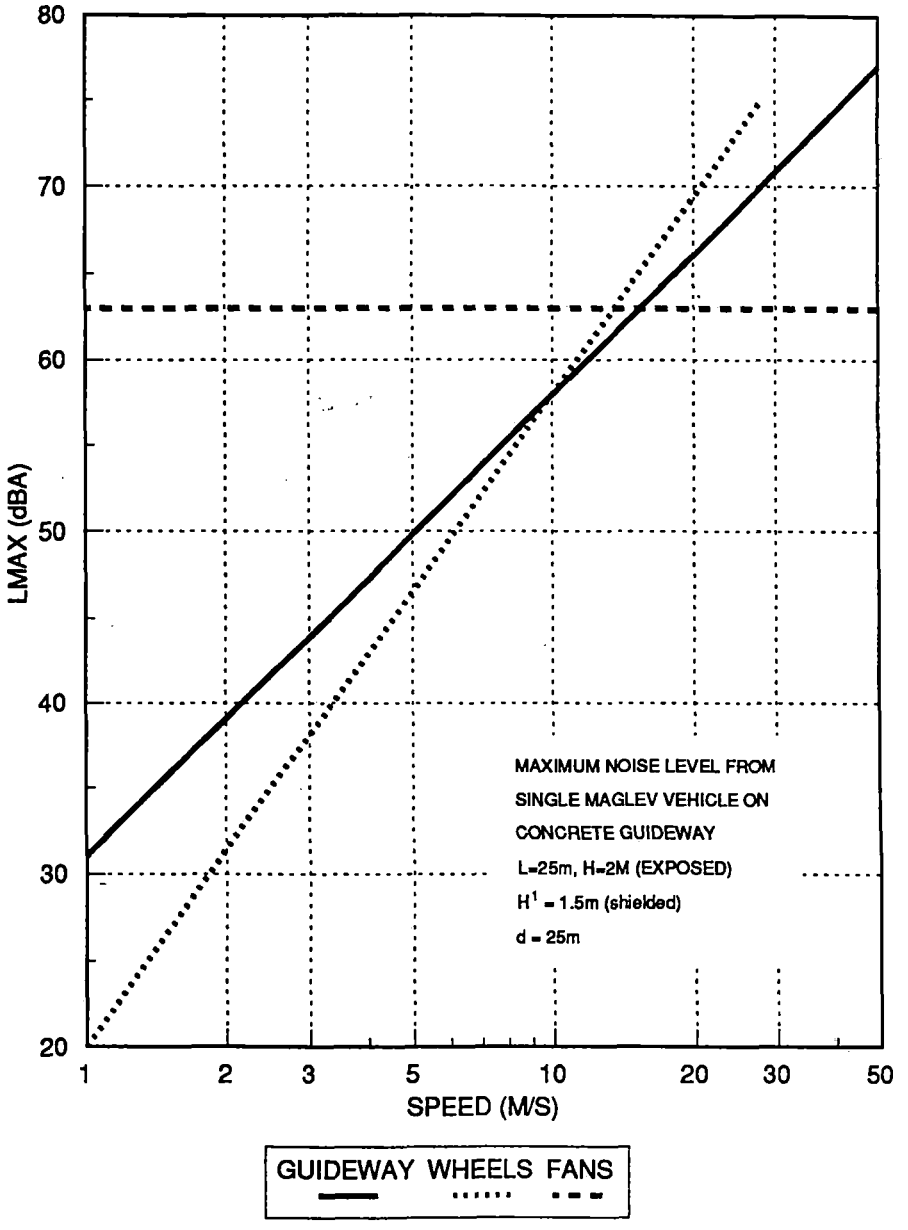

Figure 4. Maglev Noise in Low Speed Range, 0 to 42 m/s

High Speeds, greater than 150 Km/hr (42 m/s)

At speeds greater than approximately 150 Km/hr (42 m/s), the dominant noise source is of aerodynamic origin. A maglev vehicle travelling at high speed causes unsteady disturbances in the surrounding air which generate fluctuating forces and/or pressure fields. These fluctuating forces and pressures along the body cause sound to be radiated either directly from the disturbance at the airflow/body interface or by vehicle panels caused to vibrate by these forces or pressures. This type of sound production is called aeroacoustic radiation and the sources are directly related to aerodynamic disturbances. The first report in this series, "Noise Sources of High Speed Maglev Trains," describes the many air flow disturbances that can cause noise.[3]

It is important to understand that the field of aeroacoustics is very complex; there are many source types that can result in similar noise characteristics and the researcher often has little clean data with which to work. Many of the hypotheses about dominant sources are based on circumstantial evidence. For example, at very high speeds there is a component of the total noise radiation by structural radiation from vehicle body panels, but the actual contribution compared to aerodynamic sound is unknown. At this point, we assume its contribution is included in an overall equation expressing noise from all aerodynamic sources. This section discusses the expected contribution of aerodynamic sources to overall sound level for vehicle speeds greater than 150 Km/hr (42 m/s). The resulting noise vs. speed plots are shown in Figure 5.

AERODYNAMIC SOURCES King developed a formula for the integrated effect of aerodynamic noise sources distributed over aircraft bodies and applied it to maglev trains, assuming a vehicle with a relatively clean configuration.[6] King believes that the noise from the turbulent boundary layer (TBL) itself is not included in the equation because TBL is a relatively weak source in the speed range over which he analyzed data; consequently, he treats that source separately. As more is known about the contribution of individual noise sources over the surface of a vehicle, King's equation will be refined. However, it can be used to approximate the typical aeroacoustic noise from a high speed maglev.

King's full equation when applied to a clean configuration, like TransRapid TR 07, is:

$$L_{max}(aero) = 57\log_{10}\left(\frac{U}{200}\right) + 10\log_{10}\int \frac{\cos^2\theta}{r^2\,(1 + M\sin\theta)^4}\,dS_R + 82.5 \quad dBA$$

where U = speed, Θ = angle between observer and noise source, r = vector distance to source, M = Mach number and S_R = surface of vehicle.

The integral cannot be approximated by a simple expression. However, an approximation can be made by separating out a factor for convective augmentation, called "Aug." Values for Aug are given in a table below. The remaining integral is approximated by the following expression:

$$S = \int \frac{\cos^2\theta}{r^2} dS_R \approx \frac{H}{d}\{\arctan\left(\frac{L}{2d}\right) + \frac{1}{2}\sin\left[2\arctan\left(\frac{L}{2d}\right)\right]\}$$

where H = vertical dimension of radiating surface in meters,
L = length of radiating surface in meters, and d = distance to observer in meters.

For typical dimensions of a single maglev vehicle, H = 2 meters, L = 25 meters, and with the reference distance of 25 meters from the guideway, the value of S is 0.055.

Putting the equation into our standard form:

$$\mathbf{L_{max}(aero) = 57 \log_{10}(s/56) + 10 \log_{10} S + Aug + 83 \ \ dBA,}$$

$$\mathbf{SEL_{ref}(aero) = 47 \log_{10}(s/56) + 10 \log_{10} S + Aug + 81 \ \ dBA,}$$

where: s = speed in meters/second,
S = approximation for integral,
Aug = convective augmentation, with values given in Table 1.

Table 1. Approximate Values for Convective Augmentation Term

SPEED (m/s)	AUG (dB)
28	0.12
56	0.50
69	0.77
83	1.04
98	1.47
112	1.92
140	3.00

TURBULENT BOUNDARY LAYER (TBL) Noise from the TBL is difficult to pin down. On one hand, the TBL generates low sound levels per unit surface area at low speeds, and only when the surface area is large can it be measured. On the other hand, the source mechanism of TBL noise has a powerful exponential growth with speed to the 8th power. Consequently, when speeds increase to the point where TBL dominates, any further increase in speed represents a substantial increase in noise.

King has estimated an upper bound expression for the overall (not A-weighted) sound emitted by longitudinal quadrupoles distributed over the surface of a maglev vehicle.[2]

$$L_{max}(TBL) = 80 \log_{10} \left(\frac{U}{200}\right) + 10 \log_{10} \int \frac{\cos^4\theta}{r^2(1 + M \sin \theta)^6} dS_R + 78 \quad dB$$

where U = speed in Km/hr, r = distance from observer to any radiating surface, M = Mach number (ratio of vehicle speed to sound speed), S_R = area of radiating surface.

As in the case of aerodynamic sound, the expression has a surface integral containing convective augmentation. Just as discussed above, approximate expressions are used to simplify the calculations. These are summarized below:

$$\mathbf{L_{max}(TBL) = 80 \log_{10}(s/56) + 10 \log_{10} T + Aug + 77 + A, \quad dBA},$$

$$\mathbf{SEL_{ref}(TBL) = 70 \log_{10}(s/56) + 10 \log_{10} T + Aug + 79 + A, \quad dBA},$$

where: s = speed, meters/second,
Aug = convective augmentation term from Table xx,
A = factor for A-weighting the spectrum (see method below),
T = approximate expression for TBL surface integral.

The surface integral in the noise expression for TBL can be approximated as follows:

$$T = \int \frac{\cos^4\theta}{r^2(1 + M \sin\theta)^6} dS_R \approx \frac{H}{8d}[(\frac{2d}{L} \sin^2 \alpha + 3 \sin \alpha + 3\alpha]$$

where H = vertical dimension of radiating surface,
L = length of radiating surface,
d = distance to receiver,
α = 2 arctan (L/2d).

For typical dimensions of a maglev vehicle, H = 2 meters, L = 25 meters, and our reference distance d = 25 meters, the value of T is .065.

As we mention above, the original expression for TBL noise is the overall sound energy. In order to estimate the contribution to the A-weighted sound level, we need to consider the sound spectrum of TBL noise. Since the A-weighting curve discriminates against low frequencies, we need to determine under what conditions the spectrum generates enough energy to register on an A-weighting scale. Following is an approach to estimating that contribution and calculating the correction term, A, in the equation.

Researchers have found that typical spectra of pressure fluctuations on a smooth surface with a TBL have a frequency distribution that is relatively flat at low frequencies but that rolls off at high frequencies.[4] If the spectrum rolls off above a frequency f_0, then we assume it has no further contribution to the A-weighting. The point at which substantial "roll-off" begins to occur in the TBL frequency spectrum is at a Strouhal number of 1.13. The Strouhal number is a non-dimensional unit which, in the case of TBL, is:

$$S(\omega) = \frac{\omega\ \delta^*}{s}$$

where ω = circular frequency (in radians/second),
δ^* = TBL displacement thickness, meters
s = vehicle velocity, meters/second.

With S = 1.13, we can determine the peak frequency of a TBL by determining the displacement thickness of the boundary layer and the vehicle speed to get ω, and calculate frequency in Hertz from the relation;

$$f_0 = \frac{\omega}{2\pi} = \frac{1.13\ s}{2\pi\delta^*}$$

The first step is to estimate displacement thickness, δ^*. For a typical flat plate turbulent boundary layer profile, δ^* is approximately related to the boundary layer thickness, δ, by the relation:

$$\delta^* = \delta/8.$$

Boundary layer thickness can be calculated for a TBL on a flat, smooth plate by the following formula:[5]

$$\delta = \frac{0.37\ x}{(sx/\nu)^{0.2}}$$

where x = distance from leading edge of plate in meters, typically half the vehicle length,
s = vehicle speed, meters/second,
ν = kinematic viscosity of air
(at standard conditions, $\nu = 15*10^{-6}$ meters^2/second).

After determining f_0, the correction term "A" is determined from the relative frequency weighting in Table 2. As an example, if the calculated peak frequency of the TBL sound is 400 Hz, then the term "A" = -4.8 dB.

Table 2. Frequency Weighting for A-weighted Sound Level

FREQUENCY, Hz	A-WEIGHTING, dB	FREQUENCY, Hz	A-WEIGHTING, dB
50	-30.2	800	-0.8
63	-26.2	1000	0
80	-22.5	1250	0.6
100	-19.1	1600	1.0
125	-16.1	2000	1.2
160	-13.4	2500	1.3
200	-10.9	3150	1.2
250	-8.6	4000	1.0
315	-6.6	5000	0.5
400	-4.8	6300	-0.1
500	-3.2	8000	-1.1
630	-1.9	10,000	-2.5

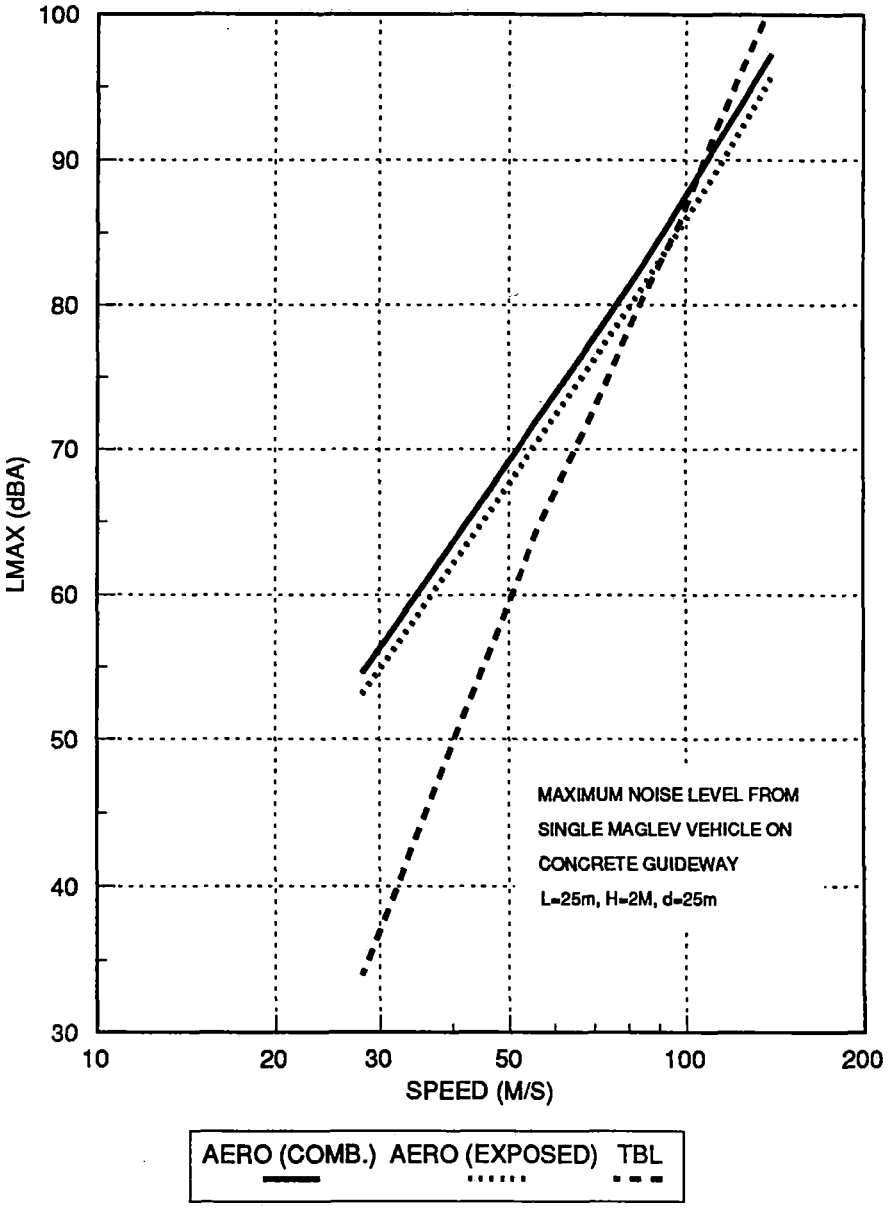

Figure 5. Maglev Noise at High Speed, greater than 42 m/s

1.3.2 Guideway

Sound is generated by vibrations of the guideway as a train passes over successive sections of the elevated structure. The guideway segments oscillate as the train successively loads and unloads each section. Low frequency vibrations of the deck structure and the supporting beams generate sound in the frequency range below 100 Hz where Table 2 shows there is little contribution to the A-weighted sound level. Higher frequency modes of guideway elements and plates can radiate sound, however, especially when they are excited by a source such as magnetic pole passing or aerodynamic loads. A detailed description of its structure is necessary to model the vibration and noise characteristics of the guideway. A semi-empirical relationship is available, however. King estimated the sound generated by vibrations of the guideway and vehicle.[6] His equations can be put into our standard form as:

$$\mathbf{L_{max}(gwy) = 27 \log_{10} (s/28) + 70 + G, \quad dBA, \ at\ 25\ meters}, \text{ and}$$

$$\mathbf{SEL_{ref}\ (gwy) = 72 + 17 \log_{10} (s/28) + G, \quad dBA, \ at\ 25\ meters},$$

where G = Adjustment for guideway type from Figure 6.

Guideway Types The type of guideway has a significant effect on the noise radiated to the wayside of a maglev system. The key variables are:

- materials making up the guideway elements,
- elevation of guideway running surface,
- presence of side walls, and
- gaps or openings along sides or deck.

Materials and Elevation. The first report in this series described the results of measurements made on different guideway types at the TransRapid test track in Germany.[3] These tests showed that noise from the TR07 vehicle was up to 6 dBA greater on an undamped steel-supported guideway than on the concrete guideway at the same speed. Similarly, noise increased by about 3 dBA when the vehicle traversed a steel switch. However, noise was about 2 dBA less on an at-grade section than on the elevated concrete guideway. These results are shown in Figure 6.

Guideway with Side Walls/Gaps. The effect of side walls is implicitly taken into account in calculating the approximations for the integrals S and T, above. Each expression has a term "H" for the vertical dimension of the radiating surface, the amount of exposed surface not covered up by the side walls. However, unless the inside surfaces of the walls are covered with sound absorptive material, the sound energy generated in the shear layers between the vehicle and the side walls and deck will escape over the top of the walls and out through any gaps. A first approximation to the sound emitted in this way is to calculate the aerodynamic noise component of the part of the vehicle covered by the wall using the equation for SEL(aero) with dimensions of the vehicle hidden by the side wall. Then adjustments are made assuming that energy reverberates without loss in the space between the vehicle and the guideway surfaces, and radiates out over the top of the wall, or through gaps and openings under the vehicle. The procedure results in a conservative estimate of the contribution to SEL from noise generated between the vehicle and guideway surface:

- Walls and deck completely sealed (e.g., drainage scuppers acoustically baffled):
    1, Calculate **SEL(shielded aero)** using dimensions of one side of vehicle shielded from direct view. (This is the portion of the vehicle hidden behind the wall.)
    2. Calculate **SEL(walls)** by subtracting 3 dBA. (This adjustment assumes that half of the sound energy generated between the vehicle and guideway surfaces that finally reaches the reference point is reduced by a combination of directivity and absorption upon multiple reflections between walls and vehicle.)
    3. Add the new **SEL(walls)** to the **SEL(aero)** for the vehicle surface exposed above the walls.

- Gaps for drainage placed at base of wall, facing outward:
    1. Calculate **SEL(shielded aero)** using dimensions of one side of vehicle shielded from direct view,
    2. Add **SEL(open gaps)** to **SEL(aero)** without subtraction of any energy.

- Gaps for drainage facing downward, or open deck structure:
    1. Calculate **SEL(shielded aero)** using dimensions of <u>both</u> sides of vehicle shielded from direct view,

2. Calculate **SEL(shielded gaps)** by subtracting 5 dBA. (This adjustment assumes that the sound energy generated between the vehicle and guideway surfaces that finally reaches the reference point is shielded from direct line of sight.)
3. Add the new **SEL(shielded gaps)** to **SEL(aero)**.

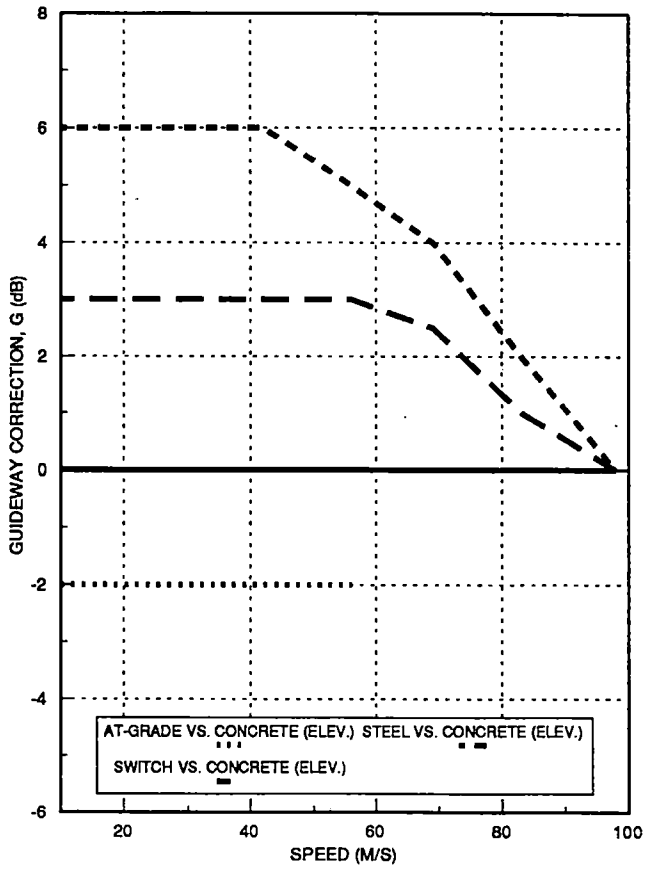

Figure 6. Guideway Noise

1.3.3 Summary of Noise Prediction Procedure

The Reference SEL for a single vehicle is the basic building block for calculating Leq and Ldn from the operation schedules. The foregoing sections show how the vehicle size, guideway configuration and material and speed determines the Reference SEL at a specific location. This section describes how to convert the SEL from a single vehicle to SEL for a train and then to go on to determine the Leq and Ldn at the reference distance of 25 meters.

SEL at a reference distance for a maglev train can be estimated from the following expression:

$$SEL_{train} = SEL_{car} + 10 \log_{10} N \text{dBA},$$

where SEL_{car} = SEL of a single car at given speed at the reference distance of 25 m (Figure 8), and N = number of cars in the train.

The Leq for an hour of operations can be determined from the SEL using the following expression:

$$Leq_{1hour} = \text{Energy Sum of all SEL's in one hour} - 10 \log_{10} 3{,}600$$

$$= \text{Energy Sum of all SEL's in one hour} - 35.6\text{dBA},$$

where Energy Sum means decibel addition of the SEL's,
and the 3,600 comes from the number of seconds in an hour.

One way of interpreting this expression is that the total sound energy is expressed in the first term, and the time period in seconds over which the sound energy is considered is expressed by the second term. This expression is used in computation methods because SEL's have been tabulated usually at a reference distance, such as 25 m, for various sources, such as automobiles, trucks, locomotives, train coaches, aircraft, etc., and the contribution of each can be added to determine the total energy in an hour.

The Ldn can then be determined from the hourly Leq's by the following method:

$$Ldn = 10 \log (\text{Energy sum of 24 hour Leq's}) - 13.8, \quad \text{dBA},$$

where Leq's occurring in the nighttime hours from 10 pm to 7 am **are increased by 10 dB** to account for increased sensitivity to noise at night. This is the building block used in the application example described in Section 1.6.1.

1.4 Propagation Characteristics

The previous section results in noise levels at a reference distance of 25 meters. The following procedure is next used to estimate the maglev noise levels at other distances, resulting in a Level-vs-Distance Curve sufficient for use in a general noise assessment. This method assumes line-of-sight unobstructed view of the guideway and with typical conditions of an elevated maglev guideway (elevated 5 to 7 meters), a receiver close to the ground (1.5 meters), and grass-covered ground between the guideway and the receiver. It is not to be applied to complicated terrain features or locations where noise-sensitive receivers are shielded from view of the guideway. Sound propagation under such complicated conditions can be estimated using procedures in FTA's Draft **Guidance Manual.**[1]

The procedure is as follows:

1. Determine the L_{dn} at 25 meters.

2. Determine Ldn at another distance using:

   L_{dn} at new distance = L_{dn} at 25 meters - 15 log (d_{new}/25), where d is in meters.

1.5 Ambient Noise Estimation

Noise from a new maglev system will add to the already existing ambient noise in the vicinity of its alignment. Our impact assessment procedure requires comparison of the future noise with the existing ambient. Ambient noise in an area can be determined by an extensive noise measurement program. However, measurements are not always available, or practical, at an early planning stage. This section provides a way of estimating the ambient noise from general data available early in project planning. For this preliminary maglev assessment procedure we will use Table 4, a simple estimate of peak hour L_{eq} and L_{dn} based on the study area's population

density, a relationship first established by the U.S. Environmental Protection Agency (EPA). The general idea is that the more people there are in an area, the more background noise from local traffic, construction projects, residential noise, etc. More detailed assessment will be required when the study area includes transportation corridors (highway, railroad, air) and any other major noise sources. A detailed method is given in FTA's Draft **Guidance Manual.**[1]

Table 3. Ambient Noise Estimates for General Assessment

POPULATION DENSITY, (people/square mile)*	PEAK HOUR Leq, (dBA)	DAY-NIGHT SOUND LEVEL, Ldn (dBA)
1-100	35	35
100-300	40	40
300-1000	45	45
1000-3000	50	50
3000-10,000	55	55
10,000-30,000	60	60
30,000 and up	65	65

* Population density is generally expressed in terms of people per square mile in the USA.

1.6 Summary of Noise Criteria for Maglev

Effect of Startle There is considerable evidence that an adjustment is required for sound signatures with rapid onset rates. The second report of this series[7] recommends that an "onset-rate adjusted day-night sound level" be used to assess noise impact from maglev operations. This unit is the Ldn contribution from maglev operations as computed from the SEL's of individual passbys, except that an adjustment is made to the SEL's for passbys with rapid onset rates. A simple adjustment is proposed for ease in application:

add 5 dB to the SEL for onset rates of 15 dB per second or more.

Figure 7 shows the relationship of speed and distance to define locations where the onset rate exceeds 15 dB per second for a maglev train. This curve was determined using a "Single Vehicle Passby Program," developed by HMMH.[8] This program accounts for divergence, directivity, convective augmentation, ground effect, atmospheric absorption and emission level (spectra) as a function of speed. TR 07 data measured by TUV Rheinland and HMMH were used to obtain the relationship shown in the figure.

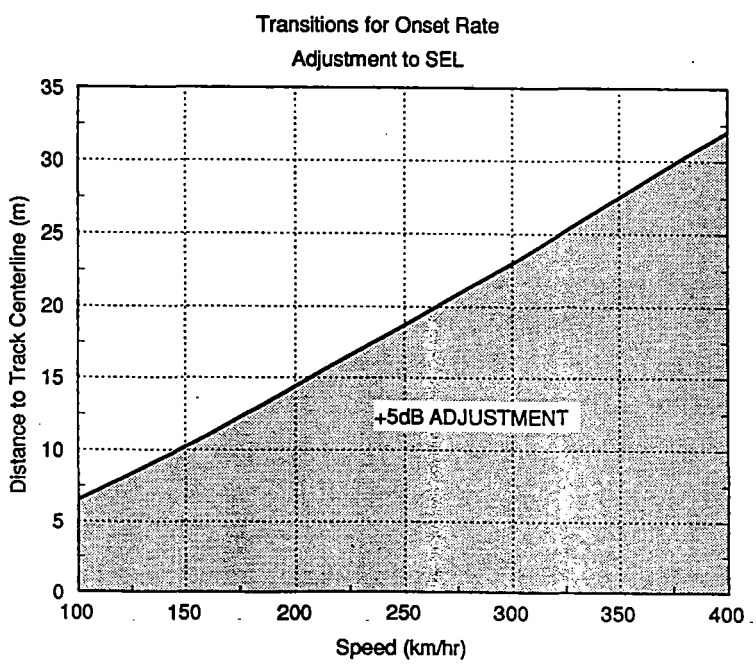

Figure 7. Adjustment for Startle from Maglev Noise

Impact Criteria The noise impact criteria for maglev operations are shown graphically in Figure 8. These criteria are based on comparison of the existing noise levels and future noise levels of the maglev operations. These criteria are identical to those proposed by the Federal Transit Administration for assessing noise impact from urban transit operations (Reference 1), with the single difference that the "onset-rate adjusted Ldn" is used for maglev operations. The noise impact criteria are defined by two curves which allow increasing maglev noise levels as ambient noise increases up to a point, beyond which impact is determined based on maglev noise alone. Below the lower curve in Figure 8, a maglev system is considered to have no noise impact since, on the average, the introduction of the system will result in an insignificant increase in the number of people highly annoyed by the new noise.

The noise criteria and descriptors depend on land use, designated either Category 1, Category 2 or Category 3. Category 1 includes tracts of land where quiet is an essential element in their intended purpose, such as nationally significant historic sites or outdoor concert pavilion. Category 2 includes residences and buildings where people sleep, while category 3 includes institutional land uses with primarily daytime and evening use such as schools, churches and active parks. For Category 2 land use where nighttime sensitivity is a factor, the noise criteria use L_{dn}. For Category 1 and 3 land uses involving primarily daytime activities, the impact is evaluated in terms of the L_{eq} for the noisiest hour of maglev-related activity during which human activities occur at a noise-sensitive location. The latter is referred to as "peak hour L_{eq}." Because the L_{dn} and daytime peak-hour L_{eq} have similar values for typical noise environments, they are used interchangeably to evaluate noise impact for Category 1 and Category 2 sites. However, because Category 3 sites are less sensitive, the criteria allow the maglev noise to be 5 decibels greater than for Category 1 and Category 2 sites.

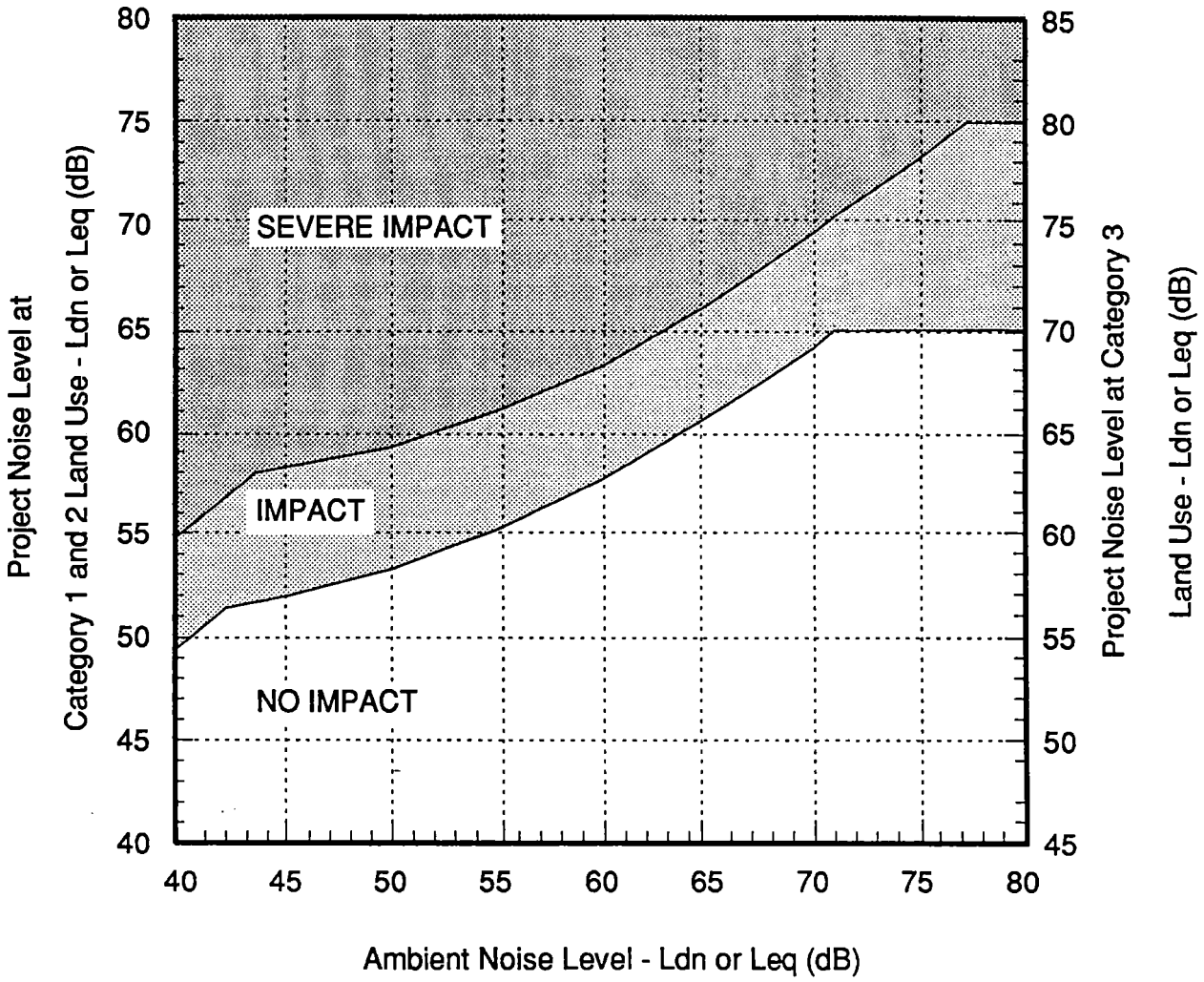

Figure 8. Noise Criteria for Maglev

The noise impact criteria are defined by two curves which allow increasing project noise levels as ambient noise increases up to a point, beyond which impact is determined based on maglev noise alone. Below the lower curve in Figure 3, a maglev system is considered to have no noise impact since, on the average, the introduction of the system will result in an insignificant increase in the number of people highly annoyed by the new noise. The curve defining the onset of noise impact stops increasing at 65 dB for Category 1 and 2 land use, a standard limit for an acceptable living environment defined by a number of Federal agencies. Maglev noise above the upper curve is considered to cause Severe Impact since a significant percentage of people would be highly annoyed by the new noise. This curve flattens out at 75 dB for Category 1 and 2 land use, a level associated with an unacceptable living environment. As indicated by the right-hand scale on Figure 8, the project noise criteria are 5 decibels higher for Category 3 land use.

Between the two curves the proposed project is judged to have an impact, though not severe. The change in the cumulative noise level is noticeable to most people, but may not be sufficient to cause strong, adverse reactions from the community. In this transitional area, other project-specific factors must be considered to determine the magnitude of the impact and the need for mitigation, such as the predicted level of increase over existing noise levels and the types and numbers of noise-sensitive land uses affected.

1.6.1 Example of Application of Criteria

For our example of noise impact from the introduction of maglev as it exists now without noise mitigation, we will look at the existing passenger train service provided in the Northeast Corridor between Boston and New York. The proposed criteria are based on Ldn which requires consideration of the noise from train passbys during daytime (7 am to 10 pm) and nighttime (10 pm to 7 am) hours separately. The example is based on a selected point along the route, a suburb of Boston where population density is 6,300 people per square mile. Residences in this area are located typically as close as 30 m from existing tracks. Urban or suburban residential areas with population density of 6,300 people per square mile are expected to have an existing ambient Ldn of 60 dBA (from Table 4). With that number as the existing ambient, the proposed criteria show that Ldn's of 58 dBA and 63 dBA from a new source would cause "impact" and "severe impact," respectively (from Figure 8).

Current 1991 Northeast Corridor service between Boston and New York has a total of 16 day

and 6 night trains passing through the suburbs of Boston. Assuming the same frequency and a similar level of service could be provided by 10 - car maglev trains with the same schedule, the SEL from the calculation in Section 1.3.1 is converted to SEL for a 10-car train at a speed of 400 Km/hr using the SEL equation in Section 1.3.3, with the "onset rate adjustment" obtained for the appropriate speed from Figure 7. For a speed of 400 Km/hr, Figure 7 shows an addition of 5 dB for sites within 32 m of the guideway.

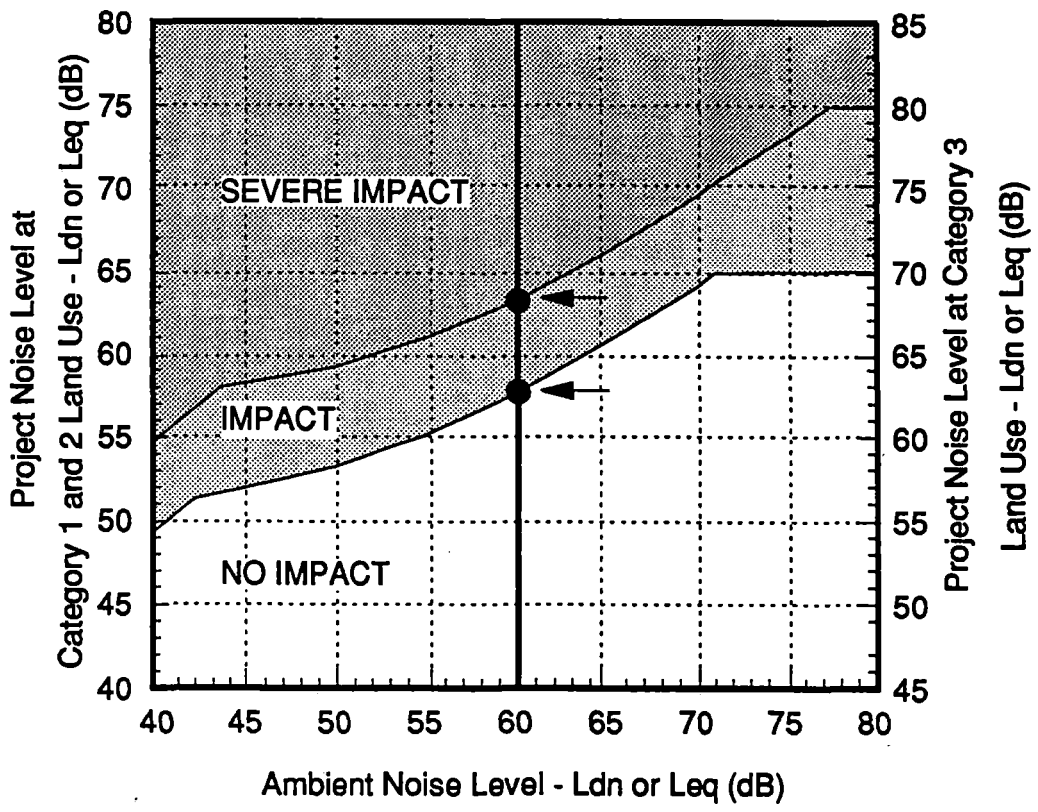

Figure 9. Example of Noise Impact Assessment

Ldn is subsequently obtained from spreading out the energy contained in 22 total events over 24 hours, but first adding 10 dB to each nighttime event (maglev passbys). The result is an Ldn of 71.5 dBA at 25 m. The line labeled "Boston suburb" in Figure 10 illustrates the distances from the guideway that would considered to be impacted using the proposed criteria. The noise propagation with distance over open terrain was taken from actual measurements at the TR 07 test track. The discontinuity in the Ldn line at 32 m occurs because that is the point at which the onset rate is expected to drop below 15 dB/sec (as shown in Figure 7). Impact would occur for any residence within 80 m of the guideway and severe impact would result for any residence within 40 m.

The method can be employed in reverse to determine the speed at which no impact will occur for a residential area. For example, if the nearest house was 30 m, the speed would have to be reduced to 267 Km/hr to fall into the "no impact" zone of Figure 10.

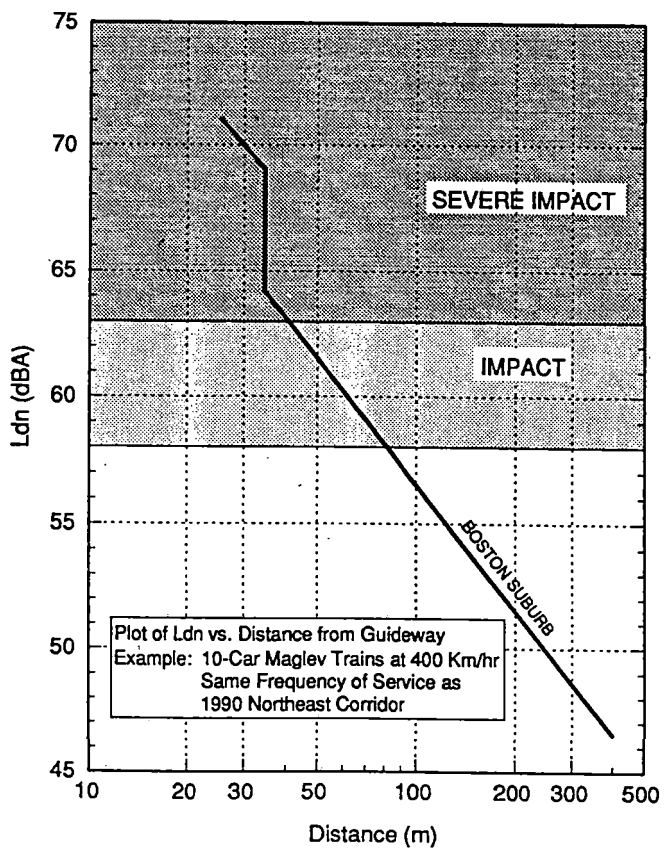

Figure 10. Ldn vs. Distance for Example

2. DESIGN GUIDELINES

This part of the report is intended to increase the awareness of designers of future maglev systems in taking noise into account in their designs. The field is too new to be able to predict the effectiveness of the noise control suggestions in all cases, but following the general principles discussed below should lead to quieter designs. They are summarized in Table 4 at the end of the section.

2.1 Guideway Structural/Mechanical

The first element of the maglev system for noise control consideration is the guideway. The guideway itself does not radiate noise without the presence of a train, but the guideway shape, material and structure details contribute to the way the it responds during the passby of a train. The guideway is the greatest expense of a new maglev system and retrofitting it for noise control features after it is built is likely to incur even greater costs, the design should take noise control into consideration at the outset. Figure 11 illustrates the elements of the guideway that are important in noise control.

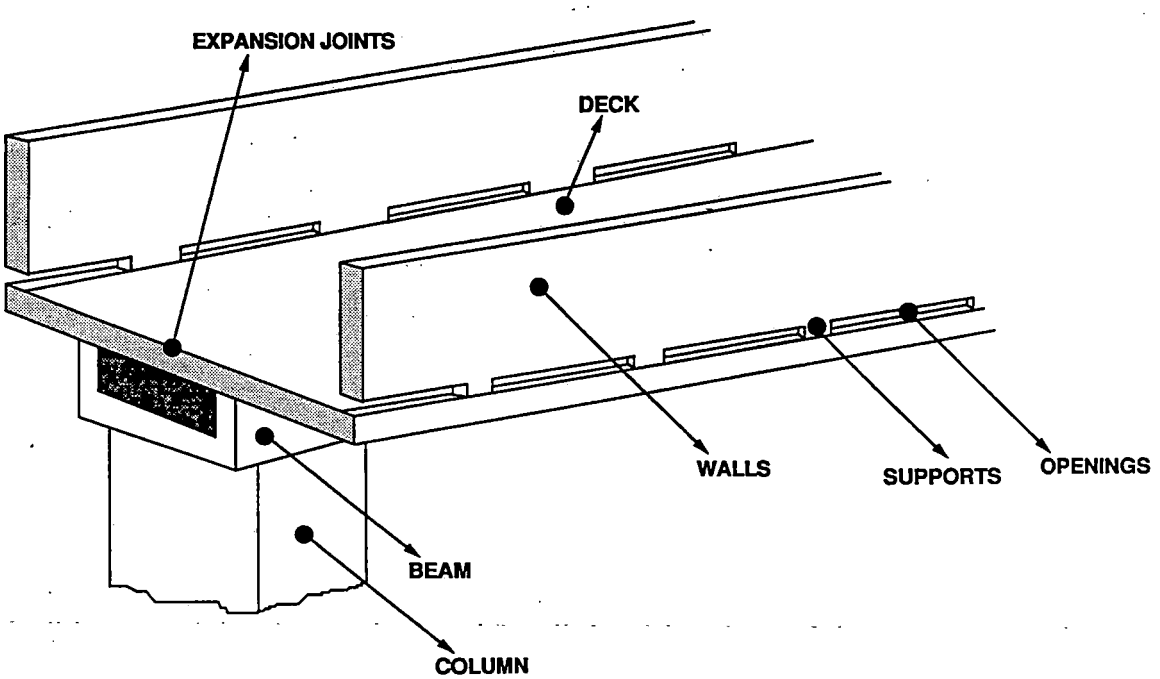

Figure 11. Guideway Structural/Mechanical Noise Sources

2.1.1 Configuration

Walls The potential benefit of side walls on the guideway structure is that they act as a noise barrier. Noise from the maglev vehicle at high speed is radiated from the aerodynamic sources distributed over the surface of the vehicle. Consequently, a fully exposed maglev vehicle will radiate more sound than one that is wholly or partially shielded from view. Guideway types with side walls, such as proposed for many EDS maglev systems, provide shielding as an integral part of the guideway design.

A disbenefit of side walls is that reverberant sound builds up between the wall and the vehicle and radiates out over the top of the wall. This reverberant sound reduces the effectiveness of the wall as a noise barrier. An effective control for this problem is to line the surface of the wall exposed to the vehicle with sound absorptive material to eliminate the build up of reverberant sound energy.

Side walls also have the potential disbenefit of acting as direct sound radiator to the wayside. This occurs when structural vibrations are induced in the walls by the gust loading and magnetic forces from the passing vehicle. The relatively large, flat surface of the wall is an efficient radiator of sound. A dynamic analysis of the wall and guideway structure will reveal the potential for structure-borne sound and should provide clues for its control.

Deck Continuous deck surfaces can be efficient radiators of low frequency structure-borne sound, especially when constructed of light weight materials. They are typically made up of large, flat panels with dimensions that are comparable with low frequency acoustical wavelengths. Increasing mass and damping will serve to reduce deck vibrations and radiated sound.

Expansion joints Wheels are used by some maglev systems for low speed vertical support. When wheels encounter discontinuities in the deck, such as expansion joints between deck segments, they radiate noise from the tire surfaces as well as cause dynamic loads to the deck with subsequent structure-borne sound. Smooth joints are difficult to maintain due to eventual unequal settlement of guideway sections. Two ways of minimizing joint impacts are the use of finger joints to minimize the surface discontinuity and of angled joints to spread the impacts in time.

Beam The supporting beam can radiate structure-borne sound in a manner similar to the side walls, depending on its shape and material. Avoiding large, flat radiating panels helps eliminate this source.

Column The supporting columns can also radiate sound depending on their shape and material. Again, large, flat radiating surfaces are to be avoided.

Gaps and Openings Openings are provided in the guideway surface to allow drainage and pressure relief. Sound escapes directly from any gap in the continuous surface, thereby defeating the effect of shielding of walls and deck surfaces. Openings should be baffled to prevent direct sound radiation to the wayside.

Supports Evenly spaced supports between gaps and openings are a potential source of vortex noise as moving air surrounding the vehicle encounters the stationary member. Periodic spacing increases the potential of developing a siren-like sound at a frequency determined by the speed of the vehicle divided by the distance between supports. Tonal sounds are extremely annoying to nearby receivers. Unequal spacing between obstructions to airflow will serve to reduce the tonal quality of the sound.

2.1.2 Materials

The selection of guideway construction materials is governed by cost considerations, although there is no choice but to place non-magnetic materials in the vicinity of the magnets. Measurements at Transrapid's test track show that a concrete guideway structure is as much as 6 dB quieter than an undamped steel structure for the same vehicle speed. Experience with rapid transit elevated structures has shown that noise from steel beams with damping treatments can be comparable to that from concrete beams. The effect of open structures of either concrete or steel remains to be determined.

2.1.3 Dimensions

The size and thickness of vibrating panels relates to the radiation efficiency, sound power and resonant frequencies. Stiffening ribs on large panels have the effect of increasing radiation

efficiency in the frequency range affecting the A-weighted sound level. Analysis of structure-borne sound characteristics of a guideway design will reveal potential sound problems.

2.2 Vehicle Structural/Mechanical

Noise is radiated from the mechanical systems and the structure of the vehicle as shown in Figure 12. At speeds below lift-off, the wheels that support and guide an EDS maglev generate noise from interaction with the guideway running surface, while at high speed, the forces generated by magnetic pole passing cause structural vibrations. Cooling fans and pumps associated with the lifting, propulsion and hotel systems radiate noise. Body panels radiate noise from structural vibrations induced by the turbulent boundary layer on the car body surface. These sources are discussed in this section.

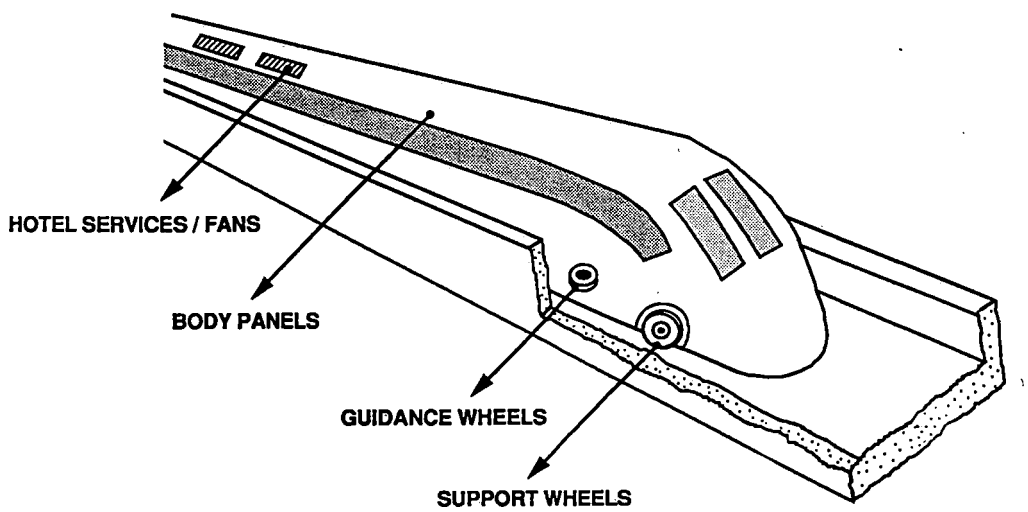

Figure 12. Vehicle Structural/Mechanical Noise Sources

2.2.1 Support and Guidance

Wheels Electrodynamic maglev vehicles are supported by wheels at speeds too low to generate enough magnetic repulsion to lift the vehicle and keep it aligned within the walls of the guideway. At speeds below lift-off, the wheels run along a smooth surface on the guideway and generate noise from interaction with the running surface. Noise is radiated partly from the guideway structure and partly from the tires. Noise from tires rolling over smooth surfaces is a subject that has undergone a great deal of research in studies sponsored by Federal Highway Administration, National Bureau of Standards and others. Extensive measurements show that tire noise is proportional to 40 log speed, and that smooth tires and cross-treaded tires are noisier than ribbed tires. Some noise is radiated from the tire casing, but the major component is generated by "air pumping" from tread and roadway cavities, with the noise directed fore and aft along the guideway. This source, of course, ceases when lift-off occurs.

To minimize tire noise on a maglev vehicle, the tires should be ribbed; regularly spaced cross bars and zig-zags should be avoided. Side walls should be well shielded from any openings in the guideway. This is especially important for the sideward-facing guidance wheels that are located near the top of the guideway walls. The running surfaces should be moderately smooth -- too smooth, and the noise increases. In fact, open-graded asphalt has been found to reduce noise on highway surfaces, due to a combination of sound absorption and pressure release at the tire/roadway interface.

Magnets At high speed, the forces generated by magnetic pole passing cause structural vibrations in both the vehicle and the guideway. These forces are periodic since the poles of magnets embedded in the guideway and those on the vehicle are regularly spaced with a defined pole pitch. As the moving vehicle encounters the fixed magnets in the guideway, sound is radiated at the pole passing frequency, f_p, where:

$$f_p = \text{speed (m/s)} / \text{pole pitch (m)}.$$

This source is tonal and can be significant in the low- to mid-frequency range (see Task 1 report for a discussion of this source).

This source of noise is not well understood. It is not clear what is the relative contributions from the vehicle and from the guideway. Further measurements should be taken on an operating maglev system to define pole passing noise and to develop means for controlling it.

2.2.2 Propulsion System

Magnetically propelled vehicles are unusual in that the propulsion system does not dominate the noise from the vehicle. It is not totally silent, however. Cooling fans, refrigeration units and other ancillary systems continue to operate as part of the mechanical system. The electronic equipment in the control system also generate a noticeable hum, increasing in frequency as the vehicle speeds up. Two other minor noise sources are associated with magnets: magnetostriction and coil vibrations. Magnetostriction is the shrinking and expanding of an iron core as the magnet undergoes flux changes. Vibration and subsequent structure-borne sound is generated in anything attached to the magnet support structure. Coil noise is generated by the vibration of the coil surrounding the magnet core as it undergoes changes in flux.

Although they are not generally among the dominant noise sources for a maglev system, each of these sources should be considered for its role in the noise radiated to the exterior (and interior) of the vehicle. Treatments for quieting fans and mechanical systems are available.

2.2.3 Hotel Systems

Systems providing light, heat, air conditioning, and amenities to improve passenger comfort are referred to as "hotel systems." Among the important noise sources in this category are the air moving devices in the heating, ventilating and air conditioning system which are most noticeable at low speeds, but contribute to the total wayside noise at all speeds. Often heat exchangers are placed just below the roof to avoid heat build-up under the vehicle. At the roof level, fan noise is unshielded, radiating directly to the wayside. Consideration of the placement of the air intakes and exhausts, as well as installation of sound-absorptive duct lining, can reduce the contribution of this noise source to the wayside.

2.2.4 Body Structure

Perhaps the most important, and least understood, structural noise source is body panel radiation. Body panels are light and flexible; they tend to vibrate as the vehicle moves. At low speed, the vibrations tend to involve whole panels as the body flexes in response to discontinuities in the guideway surface and periodically spaced magnets. At high speeds, these forces are joined by the wall pressure fluctuations caused by the TBL. Some researchers believe that body structural vibrations increase the noise radiated from the TBL. Sound radiates both outward and inward from body panels. In fact, this source is quite noticeable inside commercial aircraft, especially well forward of the jet engines.

Further research is needed on this subject to determine the importance of structural noise radiation. There may be an opportunity to develop an active vibration control system for critical body panels of a high speed maglev vehicle.

2.3 Vehicle Aerodynamics

It is generally agreed that the dominant noise sources for very high speed trains are of aerodynamic origin. Distinguishing among the many complex sources is very difficult. The mechanisms are not well understood; many of the hypotheses about dominant sources are based on circumstantial evidence from limited data. Empirical models of airframe noise have taken two approaches: one which correlates characteristics of the whole airframe with noise level, and one which combines noise from individual components making up the airframe. The former approach computes sound pressure level assuming a distribution of dipoles over the entire surface. A more detailed method relates component source strengths to component drag coefficients. For example, one group of researchers formulated a theory of airframe noise relating overall sound pressure level (OASPL) to coefficient of drag (C_D) by:

$$\text{OASPL} \approx C_D^{\,n},$$

where n = 3 for the fuselage component.[9] This relationship suggests that by reducing the drag of a maglev train, which has a similar shape to an airplane fuselage, by 25%, the sound level should decrease by about 4 dB. An important assumption for this approach to be valid is that there is a uniform distribution of sound sources over the airframe, with no particular source standing out.

A uniform distribution of sources is only an approximation and is not the usual case, especially in the case of a real vehicle. The method of adding up the contributions from each identified component, allows one to diagnose the dominant sources and prescribe mitigation measures. The following subsections focus on the various aeroacoustic sources and provides a very general discussion of their characteristics and potential controls. The location on the vehicle associated with each is shown in Figure 13.

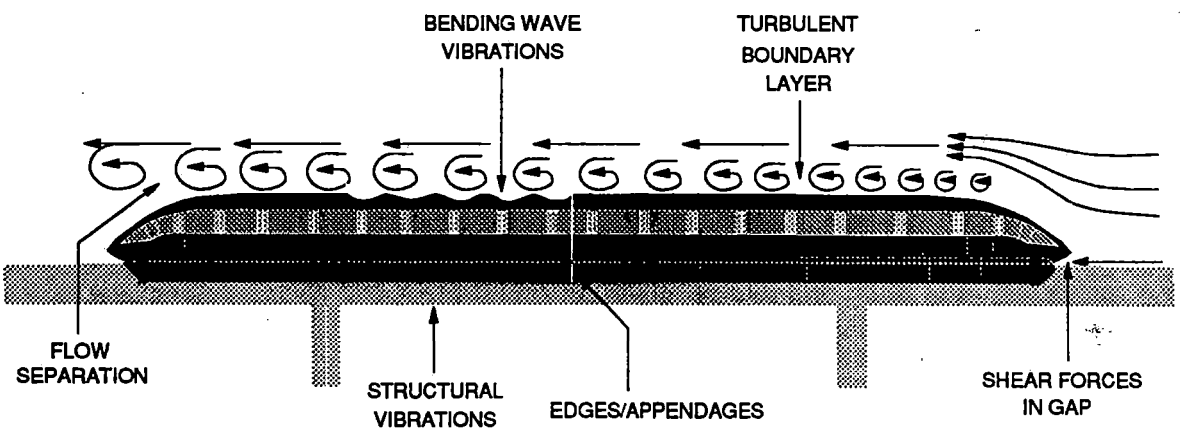

Figure 13. Vehicle Aeroacoustic Noise Sources

2.3.1 Boundary Layer

When a vehicle moves through air, it drags a layer of air along its outer surface. The air adjacent to the vehicle skin moves along with the vehicle, although it is under considerable shearing stress by the layers of air further away that are moving more slowly. This layer of fast-moving air next to the vehicle is called the boundary layer. It is the key element to nearly all the aeroacoustic sources associated with a moving vehicle. All of the following sections are devoted to some aspect of noise caused by the boundary layer. As just one example, when a moving vehicle passes a fixed obstacle like a pole or a strut, the moving layer of air is peeled off by the fixed object, and forms vortices. Given the right spacing; dimensions and air speeds, these vortices can generate pressure pulses which can radiate as sound. Other examples are given below.

2.3.2 Transition from Laminar to Turbulent

As the front of the vehicle encounters undisturbed air, a smooth (laminar) boundary layer forms as the air accelerates up to the vehicle speed. The shear stresses in the boundary layer cause the flow to break up into swirling eddies and vortices characteristic of what is called the turbulent boundary layer. The laminar boundary layer is inherently unstable, it takes only a slight perturbation for it to become turbulent. This point of transition from laminar to turbulent is a source of radiating pressure fluctuations, or sound. How much sound is generated is not well understood. It appears that sound is minimized when the transition to turbulence is orderly and is accomplished without separation.

2.3.3 Flow Separation and Reattachment

Boundary layer separation occurs when vortices and swirls in the turbulent boundary layer become so great at the surface that the air separates from the body causing a pressure deficit at that point. Separation of the boundary layer from the vehicle skin is to be avoided if at all possible. Not only is it a source of intense noise, but it increases vehicle drag. Researchers in Germany used a microphone array to locate a strong region of separation as the cause of the dominant noise source near the leading edge of the TransRapid TR06.[10] When it reattaches, the

boundary layer literally slams onto the body panels causing sound radiation from that point.

The onset of separation depends on the pressure gradient along the vehicle surface. A rapid increase in pressure forces the flow to separate, whereas a gradual increase in pressure can be overcome by the momentum of the fluid. The pressure gradient can be determined through study of the aerodynamics of the vehicle. One of the promising control methods is boundary layer suction at key locations. This treatment has been found to stabilize boundary layers, with attendant reductions in drag.[5]

2.3.4 Turbulent Boundary Layer (TBL)

After the boundary layer transitions from laminar to turbulent near the front of the vehicle, the rest of the body panels are covered with TBL. A TBL can be considered to have two or more regimes with different characteristics as distance increases outward from the vehicle. Motions of the air are nearly random in the region next to the skin of the vehicle, but further out the flow can be intermittently turbulent and non-turbulent, finally reaching undisturbed flow. The motion of air in a TBL is not totally random, however. The random velocity fluctuations and resulting pressure fluctuations are correlated over some length and time scale; a small correlated region of flow within a TBL is called an eddy, which can be considered a packet of energy with a characteristic wavelength. Research has shown that the frequency of sound radiation from a TBL is related to the dimensions of these correlated regions within the TBL, and that the intensity of sound from a TBL is related to the correlated areas of pressure fluctuations. Further, it is found that the sections of correlated flow grow larger with distance along the vehicle, with a corresponding lowering of sound frequency (the effective wavelength gets larger).*

Turbulent flow over a surface generates fluctuating forces on a body, and if the skin surface is compliant, fluctuating displacements of the surface. A vibrating surface is well known as a sound source, radiating to both the interior and to the exterior of an aircraft fuselage. Some researchers believe that vibrations of a compliant surface increase the noise radiation from a TBL. Making the surface rigid to these small scale pressure fluctuations will therefore serve to minimize sound radiation. Other researchers believe a compliant surface can be provided which

* This phenomenon can actually be experienced inside a large commercial aircraft with engines at the rear. People in window seats at the very front can hear a higher frequency rushing noise from the boundary layer than those a few seats back.

"gives way" to the pressure, thereby damping out the fluctuations. Further research is needed to determine the best way in which to handle TBL sound. Some of the ongoing research involves microgrooves in the skin, "shark skin" compliant surfaces, and active compliant surfaces.

2.3.5 Trailing Edge Separation

Noise research in the 1970's showed that fluctuations of air pressure at trailing edges of wings and flaps dominate the airframe noise component of aircraft. Deployment of flaps have been shown to increase the noise from a clean configuration aircraft by as much as 15 dB for a commercial air transport.[11] This noise source increases approximately as the fifth power of aircraft speed. A similar noise increase could occur for a maglev vehicle if wing-like control surfaces are used.

Efforts to control noise from trailing edges include installing porous skin sections, sometimes backed with sound absorbing material, at the trailing edges of wings and flaps, and at the leading edges of flaps just behind the wings. These treatments have resulted in 6 dB to 10 dB reductions in sound of the flow separation at the trailing edge of the wing. Another treatment showing promise is a sawtooth trailing edge with a resulting 3 dB to 6 dB reduction. Blowing or suction of the boundary layer at the trailing edge also shows promise, but with additional complexity.

2.3.6 Edge Noise

The articulation joint between vehicles in a train or between independently suspended panels is a discontinuity in the otherwise smooth boundary layer surface. These edges trip the boundary layer flow and establish a local region of separated flow that generate sound similar to a trailing edge. The source intensity of an edge is likely to increase approximately as velocity to the fifth power.

Mitigation of edge noise requires elimination of all discontinuities in the surface normal to the air flow. This is a difficult requirement for a train with body surface discontinuities associated with articulation. Smooth, flexible joints between vehicles and smoothly tapered edges are two potential solutions.

2.3.7 Cavity Noise

Openings in the body surface normal to the airflow cause a tonal sound called cavity noise. The sound is caused by a resonance in the cavity volume induced by oscillating airflow impinging on the rear lip of the opening. It is a very common source of sound: everyone who has produced a whistle by blowing over the top of a bottle has experienced it. On a maglev vehicle, any opening is a potential source of cavity noise. The frequency of sound is a function of cavity depth. Its intensity is proportional to velocity to the fourth power, so it is not as powerful a source as some of the others. However, the presence of cavity noise is often noticeable due to its pure tone characteristics. Among the potential candidates of this source are the open wheel wells of the landing gear and ventilation openings.

Mitigation of cavity noise is a matter of eliminating any openings normal to the airstream, which may be impractical in all cases. For example, if wheel wells are found to be a problem, they could be designed to have a cover when wheels are deployed. Another solution is to inject air from the base of the cavity to interfere with the air stream impinging on the trailing edge lip.

2.3.8 Shear Layer between Vehicle and Guideway

Airflow between the vehicle and the guideway surfaces is very complex. There are in effect two boundary layers, one associated with the vehicle and one associated with the side walls and deck surface. The result is a complicated shear layer with considerable turbulence. A confined shear layer has an unknown effect on noise generation; further research needs to be performed on quantifying the sound generation.

Another and possibly more important source associated with interaction of vehicle and guideway results from boundary layer flow interaction with fixtures and supports. Vortices are shed from each element which ordinarily pose no problem as a noise source from transient flow, but can turn into a siren when evenly spaced along the path of a fast moving vehicle. Frequency of sound from this source is related to speed divided by the spacing distance. Elimination of this tonal sound occurs by distributing supports and openings with unequal spacing.

On walled guideways, a vortex is shed from the wall edge as the vehicle passes. Whether this vortex is a significant source of noise is unknown.

Table 4. Summary of Design Considerations for Noise Control

SYSTEM COMPONENT	NOISE SOURCE	KEY PARAMETERS	POSSIBLE MITIGATION MEASURES
Guideway	Structural Radiation	Surface Area, Materials, Dimensions	Damping, Absorption, Design
	Airborne Radiation	Gaps/Openings	Baffles
Vehicle	Wheels	Tread	Ribbed Tread
	Magnets	Pole Pitch	Dimensions
		Magnetostriction	Design Detail
	Fans	Size, Openings	Ducts, Location
	Compressors	Size	Baffles, Location
	Body Panels	Stiffness	Damping, Active Control
Boundary Layer	Transition	Nose Shape	Design
	Separation and Reattachment	Body Shape	Design, BL Suction
	Turbulence	Speed	Sfc. Treatment, BL Suction, Compliant Sfc.
	Trailing Edge	Sharpness of TE	Avoid Wings or Flaps, Smooth Trailing Edge, Absorptive Edge
	Edges	Surface Discontinuity	Smooth Joints, Tapered Edges
	Cavity	Wheel Wells, Air Inlets/Exhausts	Shrouds, Air Injection
Vehicle /Guideway	Shear Layer Interaction	Speed, Proximity of Fixed Structure	Design

3. REFERENCES

1. U.S. Department of Transportation, Federal Transit Administration (formerly Urban Mass Transportation Administration), "DRAFT: Guidance Manual for Transit Noise and Vibration Impact Assessment," Report No. UMTA-DC-08-9091-90-1, July 1990.

2. U.S. Department of Transportation, Federal Highway Administration, "FHWA Highway Traffic Noise Prediction Model," FHWA-RD-77-108, December 1978.

3. Hanson, Carl E., Philip Abbot and Ira Dyer. "Noise Sources of High Speed Maglev Trains," HMMH Report No. 291550-1, BAA 191, Federal Railroad Administration, Washington, D.C., May 1992.

4. Schewe, G. "On the Structure and Resolution of Wall-pressure Fluctuations Associated with Turbulent Boundary-layer Flow," Journ. Fluid Mechanics, 134, pp. 311-328, 1983.

5. Schlichting, H. Boundary Layer Theory, 6th Ed., McGraw Hill Book Company, New York, 1968.

6. King, W.F. "The Components of Wayside Noise Generated by High-Speed Tracked Vehicles," Proc. InterNoise 90, Gothenburg,Sweden, Aug 1990.

7. Hanson, Carl E., "Noise Criteria for High Speed Maglev Trains," HMMH Report No. 291550-2, BAA-1, Federal Railroad Administration, Washington, D.C. February 1992.

8. Anderson, G.S., "Single Vehicle Passby Program," computer program developed for the National Park Service.

9. Revell, James D., Gerald J. Healy, and John S. Gibson. "Method for the Prediction of Airframe Aerodynamic Noise," Aeroacoustics: Acoustic Wave Propagation; Aircraft Noise Prediction; Aeroacoustic Instrumentation, Ira R. Schwartz, ed., American Inst. of Aeronautics and Astronautics, MIT Press, Cambridge, MA, 1976, pp. 139-154.

10. Alscher, H. "Aero-Acoustic Investigations of the Magnetic Train TransRapid TR06," Proc. Magnetically Levitated Systems and Linear Drives, The Inst. of Elec. Eng. of Japan, Yokohama, July 1989.

11. Fink, M. "Airframe Noise Prediction Method," Report No. FAA-RD-77-29, U.S. Department of Transportation, Federal Aviation Administration, Washington, D.C. March 1977.

SECTION 4

RECOMMENDATIONS FOR ACOUSTICAL TEST FACILITY FOR MAGLEV RESEARCH

TABLE OF CONTENTS

PREFACE

This report is the fourth of four reports to be prepared under U.S. Department of Transportation Contract # DTFR53-91-C-00074, "Noise from High Speed Magnetically Levitated Transportation Systems." The reports under this contract cover the following areas:

1. Characterization of Noise Sources
2. Noise Criteria for High Speed Maglev Systems
3. Design Guidelines based on Noise Considerations
4. Recommendations for Acoustic Test Facility for Maglev Research.

This report provides a summary of recommended acoustic test equipment and techniques which could be used in a U.S. test facility for maglev system development.

EXECUTIVE SUMMARY

Noise from high speed operations of a maglev system is a source of concern. The German and Japanese prototype maglev systems generate high noise levels at very high speeds. Without mitigation, a maglev system may encounter public opposition if introduced to the existing transportation system in the United States. Based on progress made by the aircraft industry there are many reasons to believe that the noise level can be brought to acceptable levels. In the case of maglev, however, research is needed to develop a better understanding of the mechanisms of aerodynamic sound generation associated with high speed operations.

A comprehensive acoustical test program should be an integral part of any full scale testing program undertaken as part of a U.S. maglev development. The primary benefit from an acoustical testing program will be a quieter maglev system. Secondary benefits include a better understanding of aeroacoustic sources and aerodynamic drag associated with high speed surface transportation systems.

Gaps in research to be filled by acoustical testing are listed in the table below, along with testing approaches to define maglev noise and vibration sources and to investigate mitigation methods.

ISSUES	TEST PROGRAMS
Aeroacoustic sources	Microphone array measurements Microphones mounted on vehicle surface
Interior noise sources	Sound intensity measurements
Vehicle structural radiation	Panel-mounted vibration transducers Microphones mounted on vehicle surface Near-field/far-field microphones
Guideway structural radiation	Sound intensity measurements Vibration power flow measurements
Vehicle/Guideway flow interaction	Scale model flow visualization Microphone array measurements
Noise barrier effectiveness	Multiple-point microphones
Boundary layer control	Scale model wind tunnel tests
Noise from rolling wheels	Scale model noise tests Full scale noise measurements in Japan
Noise from lifting surfaces	Scale model noise/wind tunnel tests
Active cancellation (Interior)	Multiple-point microphones Sound intensity measurements

Acoustical testing facilities should be included at a new test track facility to perform the foregoing research. The size and scope of such a test facility depends on the philosophy of the sponsors of the development program - whether the facility will be a support operation for tests at the test track only, or a center for acoustic research on a wide variety of high speed vehicles. Each of these approaches affects the type of staff and instrumentation for the facility, as well as the budget necessary to continue operations.

INTRODUCTION

Noise has been identified as a potential source of concern associated with the introduction of maglev to the existing transportation system in the United States.[1] The first operational maglev systems have been shown to generate high noise levels at very high speeds.[2] Although there has been only a limited amount of research devoted to noise control of maglev systems, there are many reasons to believe that the noise level can be brought to acceptable levels. Among the reasons for optimism is the progress made by the aircraft industry in research on airframe noise during the 1970's. For noise reduction to be accomplished in a similar manner for maglev, we must continue the research to develop a better understanding of the mechanisms of aerodynamic sound generation associated with high speed maglev operations.

During the development of a US maglev system, a full scale testing program will be undertaken at either a test track or a useful transportation corridor to be determined. A comprehensive acoustical test program should be an integral part of any full scale testing program. The primary benefit from an acoustical testing program will be a quieter maglev system, one that will be compatible with urban and suburban land uses. Existing systems will definitely need additional noise reduction to meet environmental noise criteria in residential areas.[3]

Secondary benefits include a better understanding of aeroacoustic sources and aerodynamic drag associated with high speed surface transportation systems. Aeroacoustic research could especially benefit because never before has there been an opportunity to study aerodynamic

noise on a land-based high speed vehicle that is not dominated by propulsion noise. In addition to acoustics, aerodynamic design of the vehicle could be directly affected by the findings. For example, experience gained from acoustical testing of the TransRapid TR06 led to an improved aerodynamic shape of the TR07.[4] In that case, acoustical scanning of the vehicle passby at speed revealed locations of sources of intense noise associated with flow disturbances. Subsequent scale model testing in a wind tunnel confirmed regions of vortex shedding near the nose as a result of shape. Modifications of the nose shape were undertaken, resulting in less noise and less drag.

Aerodynamic testing is often carried out using scale models in wind tunnels instead of costly full scale testing programs at test tracks. In some cases the acoustic testing can also be carried out using scale models in wind tunnels. As discussed in Section 1 of this report, however, there are some tests that can only be performed in full scale.

Gaps in research that could be filled by acoustical testing, full scale and scale model, during any major maglev testing program are discussed in the first section of this report. The second section describes some of the testing approaches that could be used in research activities to define maglev noise and vibration sources and to investigate mitigation methods. Finally, we present a description of the kind of acoustical testing facilities that should be included at a new test track facility.

1. NEED FOR ACOUSTICAL ANALYSIS CAPABILITIES

The first two tasks in this contract quantified the potential environmental noise problems associated with the introduction of a high speed maglev system in an urban or suburban setting. Because maglev has a great potential to serve as an alternative to aircraft as a short haul carrier between cities, the mode will of necessity be placed in densely populated areas. Consequently, noise control will be a major part of the design/development process for maglev. Before design guidelines for noise control can be developed with confidence for a new maglev system, the following issues should be resolved through an acoustic test program.

- What are the key aeroacoustic sources for each speed range?
- How much of the sound radiation generated by the boundary layer can be attributed to vehicle structure?
- How effective are boundary layer control methods in reducing noise?
- How much noise is generated by the vehicle flow interaction with guideway structure?
- How much sound is radiated from the guideway structure?
- What is the screening effect of guideway side walls?
- How much noise is generated by guide wheels rolling on guideway surfaces at low speed?
- How much noise will be generated by lifting surfaces if they are employed for guidance purposes?
- How effective is active sound cancellation for maglev interior noise?

Approaches to investigating the foregoing issues are discussed in Section 2. This section discusses why these acoustical research issues are likely to be important during the development program.

1.1 Identification of Noise Sources

The aircraft industry made great progress in controlling jet engine noise after many years of research on noise generation mechanisms. However, research on airframe noise sources is proceeding slowly. Much of the airframe noise control research considered to be so important in the 1970's has been discontinued as a result of funding cutbacks in the 1980's, according to Crighton.[5] Unfortunately, it is the airframe noise sources that are key to understanding the noise generation mechanisms associated with maglev. As shown in Figure 1, noise sources originate from the magnetic propulsion system, mechanical/structural interactions and aerodynamic forces. Defining the contributions from each source makes a difference in determining the appropriate design mitigation measures. The first report prepared under this contract summarized what is known about the noise levels and sources associated with high speed maglev operations.

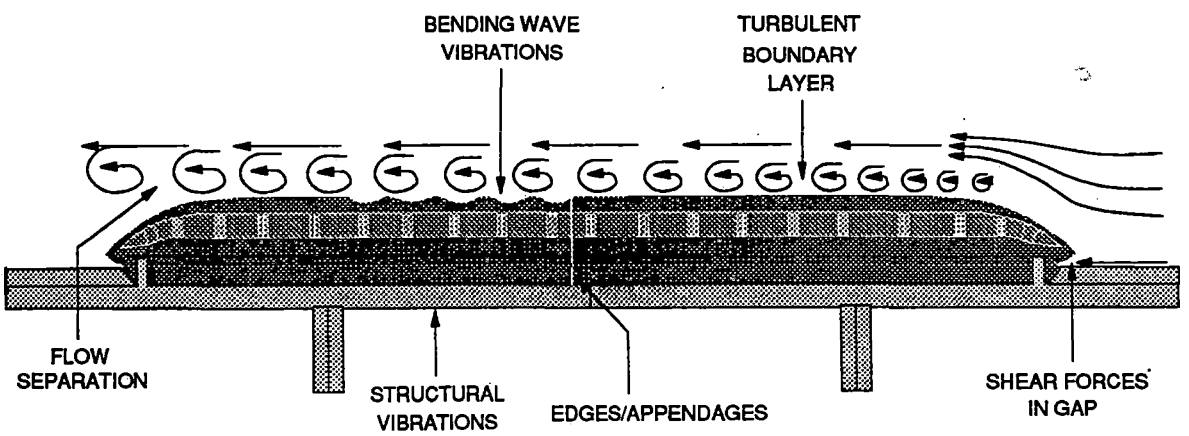

Figure 1. Maglev Noise Sources

One of the points emphasized in the Task 1 Report is that the sound generating mechanisms associated with a high speed vehicle are complex. Many different mechanisms can result in similar noise characteristics. Researchers without access to an experimental vehicle have little definitive data with which to work; often just the maximum passby level in A-weighted sound level. Consequently many of the hypotheses about dominant sources are based on circumstantial evidence. For example, the noise vs. speed curve from measurements of the TransRapid TR07 shown in Figure 2 can be approximated by three straight lines in different speed regimes with slopes proportional to velocity to the third, sixth and eighth powers, labeled A, B, and C, respectively. These three noise vs. speed relationships correspond to:

(A) noise from guideway structures (velocity to the third power),

(B) noise from vortex shedding and vehicle body radiation (velocity to the sixth power),

(C) noise from the turbulent boundary layer (velocity to the eighth power).

The straight lines shown in Figure 2 are not unique. Others could be drawn to approximate the same data because the actual sources that are dominant in each regime are not actually known.

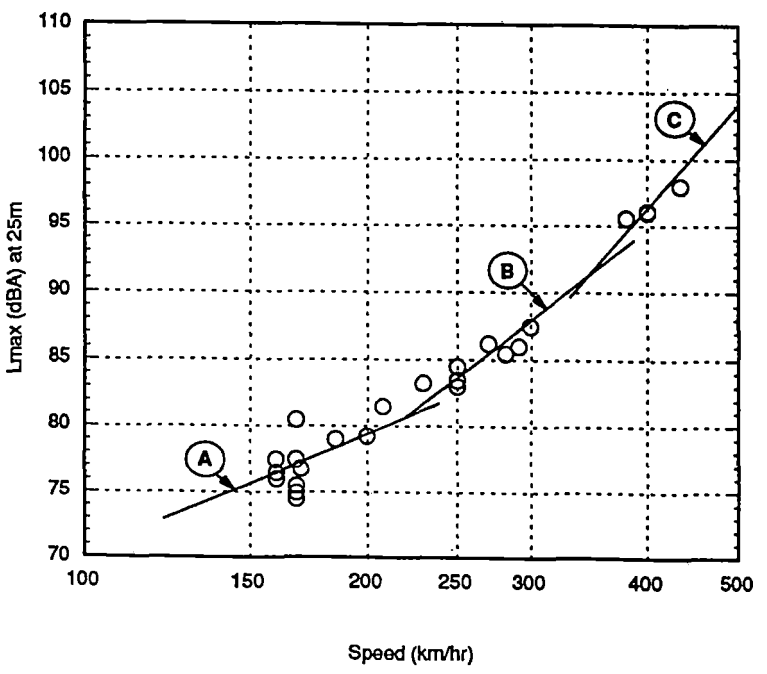

Figure 2. Measured Noise of TR07 with Straight Line Approximations

1.2 Design Input

The shape and structure of the vehicle and guideway are developed during the system design phase. An understanding of the basic noise generation mechanisms will enable designers to include noise control features in the initial design of the system instead of having to employ retrofit treatments later. Modifying an existing vehicle or guideway structure to solve a noise problem is expensive and often adds undesired weight to the system. Furthermore, since many of the airflow disturbances that generate noise are also sources of increased drag, a design that results in low noise may also result in low drag. The following subsections discuss how an acoustic testing program could provide input to the design process of a new maglev system.

1.2.1 Noise Control

Minimizing noise from a new maglev system requires incorporation of noise control during the design phase. Two examples illustrate how an understanding of the basic mechanisms of noise generation could be worked into the system. First is the turbulent boundary layer interaction with the vehicle surface which may be responsible for the rapid rise in noise with speed, e.g., proportional to velocity to the sixth and eighth powers. An issue to be resolved is whether the surface panel response is a major contributor to the sound radiation. A measurement program to determine the role played by panel vibration would be valuable. If it turns out that vibrations of the vehicle skin are important, then a reasonable noise control method is to add damping material to the surface skin. If not, then the added weight of the damping material would be unnecessary.

A more refined approach to the problem of vehicle surface radiation is based on aeroacoustic theory. Turbulent boundary layers contain quasi-random pressure fluctuations; the pressure spectrum shows some characteristic peaks, one of which corresponds to the effective convection velocity of the turbulent field. These pressure fluctuations in turbulent flow over a flat infinite plate surface, either rigid or compliant, theoretically radiates sound inefficiently (quadrupole radiation), but if the flow excites the structure and there are non-uniformities in the surface, the surface radiates sound quite efficiently (dipole radiation). Non-uniformities include stiffeners and ribs supporting the surface panels, abrupt terminations as in edges, surface curvature and roughness elements.[6] The design implications of the theory are in the spacing of ribs supporting light weight panels, as well as the materials and

dimensions of the panels. It is a given that a maglev vehicle should weigh as little as possible. A light weight skin system tends to vibrate easily in resonant modes and if the turbulent boundary layer excites the panels at resonance, then they tend to radiate more sound. However, by knowing the modal characteristics of the vehicle structure along with the frequency characteristics of the turbulent boundary layer, the designer can fine tune the vehicle structure such that frequencies of resonant modes of panels do not coincide with peak frequencies of pressure fluctuations occurring in the boundary layer. In this way the designer maintains a light weight design, but avoids sound radiation from vehicle surface panel response.

A second example is the potential use of lifting surfaces for vehicle guidance and control. Vortex shedding from trailing edges and ends of lifting surfaces are major noise generators on fixed wing aircraft. If such aerodynamic control surfaces are incorporated into the design of a future maglev vehicle, as proposed for some concepts, it is likely that significant noise radiation will result. Airframe research has resulted in noise control treatments at the leading and trailing edges that could be incorporated in the design.[5] Some treatments discussed by Crighton (Reference 5) and in the Task 3 Report of this contract include boundary layer suction and perforated and slotted edges.

Other noise control measures should be tested as part of the acoustical testing program. Among these are noise barriers, boundary layer controls, and active sound cancellation. Measurements of noise on the Japanese MLU002 maglev vehicle indicate that this vehicle radiates about 5 dBA less noise to the 25 meter wayside reference position than does the German TR07 at 300 Km/hr. A possible explanation for the lower noise level is that the side wall and closed deck guideway configuration acts as an effective noise barrier for wayside noise. Our Task 3 guidelines report gives an estimated 5 dB reduction for a noise barrier in a screened configuration.

The dominant aeroacoustic sources all relate to actions of the boundary layer such as vortex shedding, turbulence and separation. Therefore noise control methods should focus on keeping the boundary layer attached to the vehicle surface and as smooth as possible. One of the controls which shows promise for noise reduction is boundary layer suction to keep the boundary layer attached to the vehicle sides. The excess air could be ejected at the rear of the vehicle to compensate for the pressure deficit at that part of the vehicle, thereby reducing form drag.

Active sound cancellation is always under consideration as a new noise control method. The basic principle of this method is that since they are made up of periodic pressure fluctuations above and below atmospheric pressure, sound waves can be canceled out by introducing pressures of the opposite sign. The key to sound cancellation is the word "periodic." Before a sound wave of opposite sign can be introduced, the initial wave must be sampled so that a pressure generator (loudspeaker) can be set up to produce the necessary sound. Most of the external sounds from a high speed vehicle are not periodic, however. Little progress has been made on reducing broadband noise by this method.

Interior vehicle noise patterns are often characterized by tones generated by electronic equipment, air conditioning fans and other equipment with periodic operating characteristics. Active sound cancellation has been successfully applied to interiors of automobiles, trucks and locomotives. It could be useful in developing a quiet maglev system since many of the operational characteristics of maglev are likely to generate interior sound spectra with tones.

1.2.2 Drag Reduction

Minimizing aerodynamic drag is among the design goals of the maglev system development program. Measurement of noise can help meet that goal. Sources of aerodynamic noise are regions of unsteady airflow over the maglev vehicle and its guideway. Unsteady airflow over the surface of a vehicle is also associated with increased drag. As a maglev vehicle moves through air, the boundary layer of air adjacent to the vehicle starts out smoothly at the nose (laminar flow) but gradually changes to unsteady fluctuations (turbulent flow) where the nose section transitions to the parallel side body and roof of the train. Depending on the body curvature associated with forward sections of the vehicle, the transition to turbulent boundary layer flow can be gradual or intermittent. If intermittent, the flow is unsteady, with intermittent vortex shedding which draws energy from the smooth forward motion of the vehicle thereby increasing drag. Thus it is important that aeroacoustic and aerodynamic testing should be carried out in concert during development phases of a new maglev system.

A case which demonstrates how acoustical testing can lead to aerodynamic improvements occurred during the development of the TransRapid TR07.[4] Extensive acoustical measurements were conducted to locate noise sources on the prior generation model TR06. Among the measurements at the Emsland test track performed by the developers,

Messerschmitt-Bolkow-Blohm Gmbh (MBB), were a series of acoustic scans using a microphone array system (microphone array systems described later in this report). The results of the scan represented by Figure 3 indicated locations of high noise levels at a specific region near the nose of the train and at gaps between car body and magnet sections (called "bogies") and between the two cars of the train. The shaded contours superimposed over a sketch of the vehicle in Figure 3 represent regions in which the sound pressure level is uniform within a few decibels. Wind tunnel tests confirmed that the dark region at the base of the nose section corresponds to an area of intense flow separation at a crease between the vehicle body and the bogie fairings. Design changes from these investigations resulted in a redesigned nose section, smooth fairings between the car body and the bogies and elastic fairings at the joints between car bodies.

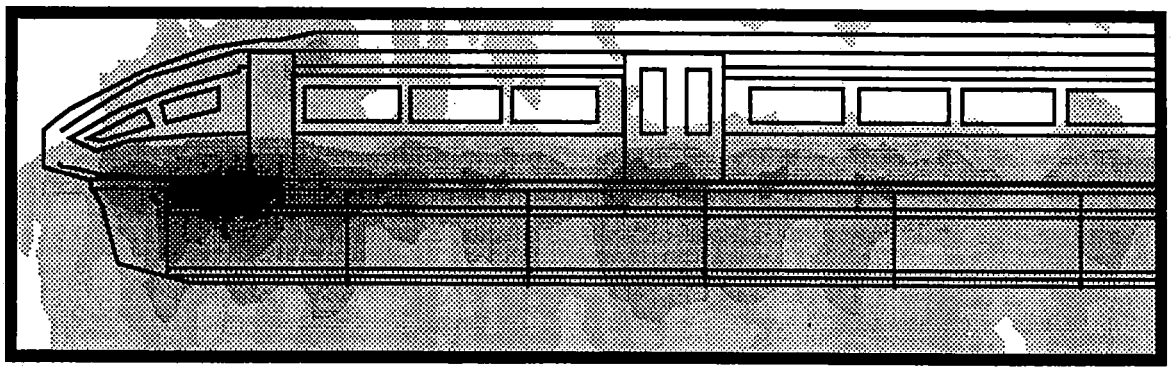

Figure 3. Locations of TR06 Sound Sources from Microphone Array Analysis

1.2.3 Guideway Structure

Noise from the guideway structure can be generated in several ways, three of which are:

- structural vibrations of girders or deck caused by vehicle dynamic loading,
- structural vibrations caused by magnet pole reactions, and
- aerodynamic interaction between vehicle and structure.

A noise measurement program will provide useful design input to identify the cause of structural noise in all three cases.

Structure-borne Noise As a train passes over guideway segments, each section oscillates as it is loaded and unloaded. Low frequency vibrations of the deck structure and the supporting beams generate low frequency sounds which may prove to be annoying to nearby residents. The guideway structure is subjected to another source of vibration at the same time -- the dynamic loads associated with magnetic pole passing. Every magnetic pole that supports the vehicle weight has a transient load during the vehicle passby. The sequential loading of magnets results in oscillating loads on the structure, resulting in dynamic response at the forcing frequency and the natural modes of vibration.

For the case of noise radiation from structural vibrations, the source of sound can be determined by a series of measurements combining vibration transducers and near field microphones. Locating the sources of guideway noise, dynamic loading or magnetic pole vibration, and treating them in the initial design can be especially important due to the relatively high cost of the guideway component of a maglev system. Knowing whether steel beams require damping treatment before being used in a given alignment could be an important factor in estimating the weight and cost of a system. It is better to have this input at the onset of the design process than after the structure is built. Retrofitting a noisy steel guideway is costly.

Aerodynamic Noise Air being dragged along with the vehicle and being pushed aside as a vehicle passes, encounters the fixed guideway structure. Obstructions to the freely flowing air cause disturbance in the flow which can result in noise generated from vortices. Evenly spaced openings, poles or structural members are the potential source of periodic vortex shedding as a vehicle moves along the guideway. The result could be similar to a very large

siren. Depending on the passby rate, the sound generated by this source could be in the frequency range of audibility showing up as a tone superimposed on the sound radiated by guideway vibrations. Since tonal sounds tend to cause greater annoyance than broadband noise, a guideway system with periodic vortex shedding characteristics should be avoided. Noise measurements should be able to identify the source of any tone that occurs and changes in the design could be specified.

1.3 Scale model vs full scale testing

A comprehensive research program on noise from high speed vehicles can take place both in the laboratory and at a test track, depending on the nature of the sound source. Some kinds of testing are best performed in a scale model facility where design changes can be made easily and cheaply. Other kinds of research are impossible to perform on less than full scale and require the prototype vehicle to operate up to speed on a test track. Some of the advantages of each type of testing are summarized in this section.

Scale Model Testing Scale model wind tunnel testing is a standard experimental tool in the field of aerodynamics. Based on the principle of dynamical similarity, airflow around a scale model is the same as for the full scale prototype provided that the dimensionless Reynolds number is the same.*

The primary advantage of scale model testing is that it allows one to economically study the relationships among key parameters and to evaluate the effects of design changes. Because they are of a size that can be handled easily, scale models save time in construction and measurement. Experiments can be undertaken in a controlled environment that is conducive to obtaining the desired information. For example, boundary layer separation and reattachment points on a maglev vehicle can be determined through flow visualization means in a wind tunnel.

As discussed in Section 1.2.2, several important changes in the shape of the forward section of TransRapid 06 were made as a result of wind tunnel tests of a 1:25 scale model. A region of vortex shedding in a sharp crease near the nose was observed by flow visualization techniques. The crease was filled in on the model to eliminate the source of vortex

* Reynolds number, $Re = LU/\nu$, where L = representative length of model (m), U = velocity (m/sec), ν = kinematic viscosity of fluid (m^2/ sec).

shedding. Further wind tunnel testing led to refinements in the nose shape to reduce flow perturbations causing drag. Implementing and testing these changes on a full scale model would have been time consuming and costly.

Where investigations of aerodynamic flow around the vehicle are expected to lead to identification of aeroacoustic sources, a laboratory with the appropriate low-noise, low-turbulence wind tunnel is most suitable. Aeroacoustic phenomena that are fluid related, such as sound from vortex shedding from rigid structures, can be successfully scaled provided both the Reynolds number and the Strouhal number are the same as full scale.** Sound pressure spectra under these conditions will be acoustically similar to the full scale situation, provided the frequency is adjusted by the scale factor.

More complicated, however, is the case of modeling sound radiation from vibrating structures and panels. Two wave-bearing media, the air and the structure, are involved. Acoustic scaling in air is well understood. The important phenomena associated with sound waves, such as reflection, scattering and absorption, are related simply by the geometric scale factor. However, the structure is more complicated. It supports a number of different types of waves: bending waves, compressional waves and torsional waves. Bending waves tend to be the most important for sound radiation, but the other types are important for modeling the correct behavior at boundaries, such as panel supports. In order for scale models to be useful, the behavior of all wave types in the structure and the associated sound radiation should be the same in the scale model at the scale frequency as occurs in the full scale prototype at full scale frequency.

Fortunately, the equivalency of scale-model and full-size testing is achieved under the following conditions:

- model and prototype materials and their surrounding fluids (air) are the same,
- loss factor (measure of damping) of structural material is independent of frequency,
- linear dimensions of model are 1/n times the full scale dimensions, and

** Strouhal number, $S = fL/U$, where f = acoustic frequency (sec^{-1}), L = characteristic length (m), and U = velocity (m/sec).

- all vibration and acoustic measurements are made at n times the full scale frequency.

It turns out that all the key parameters necessary to define structural sound radiation can be measured on a scale model that is a 1/n-size replica of the full size structure. Among the key variables that can be measured are:

- Mechanical power input
- Amplitude and modal structure of the vibration field
- Reflection of waves at structural joints
- Directivity of sound radiation
- Radiation efficiency, and
- Shielding and diffraction effects.

Under the foregoing conditions, the amplitude of vibration velocity and the amplitude of the radiated sound pressure from the model will be the same as the full scale if the input force on the model at scaled frequency is $1/n^2$ times that of the full scale input force. Scale models work well for panels and structures excited by point or localized forces. For example, a scale model of the guideway structure could be used to estimate the sound radiation from various beam configurations. Unfortunately, scale models do not work out as well for panels excited by turbulent boundary layers where the size and strengths of the turbulent eddies are difficult to scale down to miniature dimensions.

Full Scale Testing As mentioned above, scale model testing would be the ideal method of aerodynamic noise testing except for one important fact. Dynamic response of structural elements associated with a vehicle skin does not scale in the same proportions as the fluid dynamics when the real materials are used in air. Consequently, in order to determine the contribution of the structure to aeroacoustic noise from a maglev vehicle, testing must be carried out on full scale components in wind tunnels or on the prototype vehicles.

Moreover, the structure-borne transmission of interior noise sources are difficult to model. Vibration isolation and damping parameters are complex to model on less than full scale. Components can be made up and tested to optimize treatments before they are installed in

the full scale vehicle, but even then they need to be tested in the full scale configuration.

2. RECOMMENDED ACOUSTICAL TESTING PROCEDURES

Several noise and vibration measurement techniques exist to determine the behavior of sound sources. New methods are being developed as improved instrumentation becomes available. This section is by no means an encyclopedia of all the possible measurement and analysis methods available to study aeroacoustic sources. Here we review currently available methods that should be a part of the maglev noise research program, especially the full scale testing of a prototype vehicle. Like the first generation German and Japanese maglev programs, the US effort will develop a prototype and will improve it by testing. Both exterior and interior noise measurements will be part of the testing program to identify noise sources.

2.1 Noise measurements

2.1.1 Exterior diagnostic tools

Exterior moving vehicle noise measurements are made with one or more microphones mounted at specified locations from the path of the passing vehicle. For vehicles on fixed guideways, the path is determined, thereby simplifying the description of the location of the vehicle with respect to the measurement point. Depending on the purpose of the measurement, the noise will be received by a single microphone or a set of multiple microphones.

Single point microphone - A single microphone is usually employed when the data are to be used for complying with vehicle noise specifications, enforcement of noise emission regulations, noise monitoring for environmental assessments, and general noise descriptions of the envrionment. The advantage of a single microphone measurement is simplicity. Nothing more elaborate is necessary when a general description of the noise environment is required because a single point receiver represents the noise exposure of an observer at the microphone location. The disadvantage of the single microphone in the case of a fast moving vehicle is that it integrates the effect of all the sound sources and therefore can not

be used as a method for localizing individual sound sources. Moreover, the frequency content of the data is smeared by the Doppler effect***, unless corrections are made during post-processing the data. Therefore, the single point microphone has limited use in diagnostic work concerning a moving vehicle.

There are methods of using single point microphones for focusing on sound sources. The familiar "shotgun microphone," used in enhancing televised sporting events, employs a dished receiver to focus sounds coming from one small source to a microphone located at the focal point of the dish. Such a receiver could be useful in diagnostic work to locate sound sources on fixed structures, like the guideway, but a number of disadvantages are associated with the "dish" for use with fast moving vehicles. It has a relatively limited frequency response for a given dish shape: for investigating sources with a wide frequency range, the shape of the reflector must be changed, or a number of different units must be used. For focussing on a particular spot, the entire dish must be swiveled to follow the course of the moving vehicle requiring a complex mechanism. Even then, only one spot at a time can be followed for a given passby. The difficulties of using the dished microphone make it unworkable for diagnosing sound sources on the high speed maglev vehicle. However, it does have potential application in determining sound generation from particular sections of the guideway as the vehicle passes or as the guideway is driven by a controlled source of vibration.

Another single point microphone technique for measuring noise sources on the guideway is the sound intensity probe described in the section on "Interior diagnostic tools." Radiation of sound from vibrating structures can be diagnosed by this method using steady state forcing vibrations. Although transient vibrations from a moving vehicle are the actual source, structure-borne sound measurements are more easily analyzed using continuous vibration sources, such as a shaker.

*** The Doppler frequency shift is the continuous change in frequency of sound emitted by a moving vehicle as it approaches and then recedes from a fixed observer. The mathematical expression for the effect is $f = f_s/(1 - M_s \cos \Theta)$ where f is the observed frequency, f_s is the emitted frequency from the moving source, M is the Mach number and Θ is the angle between the forward vector of the vehicle motion and the vector from the sound source to the receiver. For example, when a moving vehicle is approaching the receiver, the angle Θ is less than 90 degrees and the observed frequency is greater than that actually emitted. At $\Theta = 90$ degrees, the source is perpendicularly opposite the receiver and the observed frequency is true. Similarly, at Θ greater than 90 degrees, when the vehicle is receding from the observer, the observed frequency is lower than that emitted.

Multiple microphones - A useful technique for diagnosing sound sources is to measure and record the sound at several locations around the vehicle simultaneously. Placement of microphones equidistant on a vertical plane around a source is commonly used to determine directivity in that plane and in the case of a line source like a maglev train, the sound power. Other than the complexity of setting up, calibrating and recording sound on a multiple channel tape recorder, sound power and directivity measurements are rather straightforward in that no attempt is made to correlate the signals of the various microphones. The energy average over the period of the passby is sufficient.

Microphone arrays - Microphone arrays can be used to both localize the sound sources and to correct for the Dopler frequency shift associated with a high speed moving vehicle. Arrays have been successfully applied in Germany and Japan for the identification of sound sources on high speed trains.[7,8,9] For a linear array, a line of equally spaced omnidirectional and phase-matched microphones is pointed toward the passing vehicle. The signals generated by sound pressure waves received by each microphone are recorded on individual channels of a multi-channel tape recorder (Figure 4). The sensitivity of the array depends on the angle of the approaching sound waves and a number of other factors, such as the number of microphones, their spacing, the acoustic frequency and the weighting factor multiplying the signal from each microphone (called "shading"). Summing the output of all the microphones results in a beam pattern where the group of microphones has an increased sensitivity to sounds coming from a small area, much like the "shotgun microphone" described above. By shading the microphones at the ends of the array, the beam pattern is narrowed in the center so that waves from off the beam axis have less effect. The utility of the array is that the beam of maximum sensitivity can be electronically steered to pick up sounds emanating from a wide angle in the plane of the array, similar to a searchlight. In fact, a German promotional publication recently called its microphone array, "Die akustische Taschenlampe" - the acoustical flashlight. The "searching" is done during post processing of the recorded data; the array is "steered" by the technique of controlled phase delay between each channel (Figure 5). Correlating the location of the moving vehicle with the direction of the beam is important. A dedicated channel of the tape recorder is used to record position information of the moving vehicle, such as the time of crossing a light beam.

Discrimination among wavelengths by an array depends on the distance between microphones. Different microphone separations must be used for investigation of different frequency ranges. Since a linear array can only be steered in the plane defined by its

physical axis and its acoustic axis, longitudinally spaced sound sources can be located only by a horizontal array and the vertical distribution of sound sources can be located only by a vertical array. With two axes used simultaneously in a crossed array, a mapping of sound sources over the surface of a moving vehicle can be obtained, as shown in Figure 1. Crossed arrays are now in use in both Germany and Japan [10].

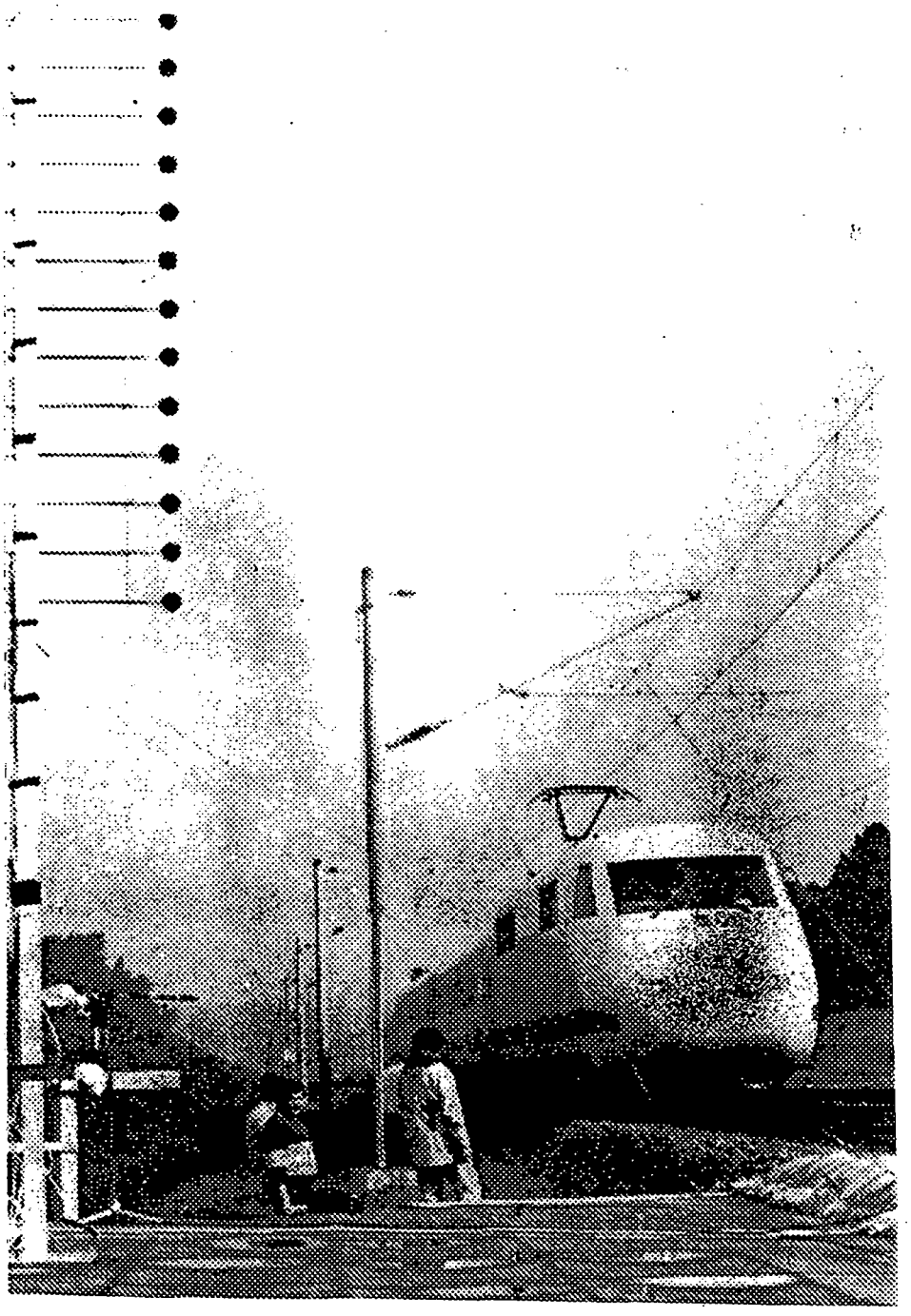

Figure 4. Linear Microphone Array (from Ref. 9)

The crossed array is among the first tools that should be developed for the U.S. Maglev Acoustical Test Facility. The state of the art of digital electronics has advanced a great deal since the first linear arrays were built in Germany in 1978. The ability to scan the surface of a fast moving vehicle and mapping the noise sources on a color monitor will be useful for both noise control and aerodynamic analysis.

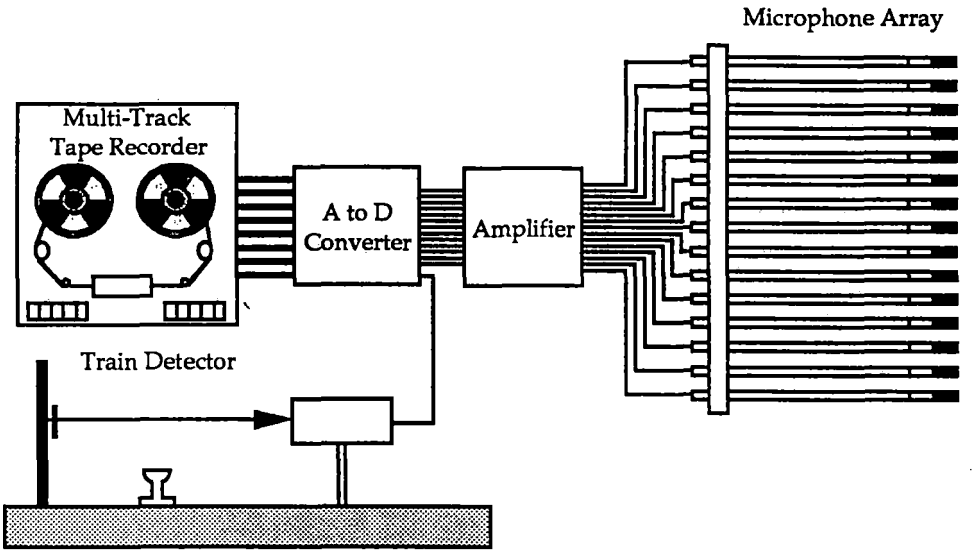

Figure 5. Schematic of Microphone Array System

2.1.2 Interior diagnostic tools

Sound intensity - A recently developed acoustical measurement technique involving multiple microphones is measurement of sound intensity. By measuring and integrating the sound pressure gradient and velocity by closely spaced phase matched microphones, the sound intensity vector (magnitude and direction) can be mapped in the vicinity of a sound source.[11] This technique proves to be especially valuable in identifying and locating sound sources (Figure 6). By moving the sound intensity probe over the surface and mapping the results onto a grid, regions of high sound intensity can be identified as sources. Further, the direction of the energy flow can be mapped through the use of the probe's directivity pattern.

Application of sound intensity appears to be confined to fixed sources, due to the time it takes to map out the isointensity contours and vectors. Sound intensity measurements could be used to determine sources of interior noise of a moving vehicle, however, provided steady state conditions can be established for long enough to scan the appropriate surfaces.

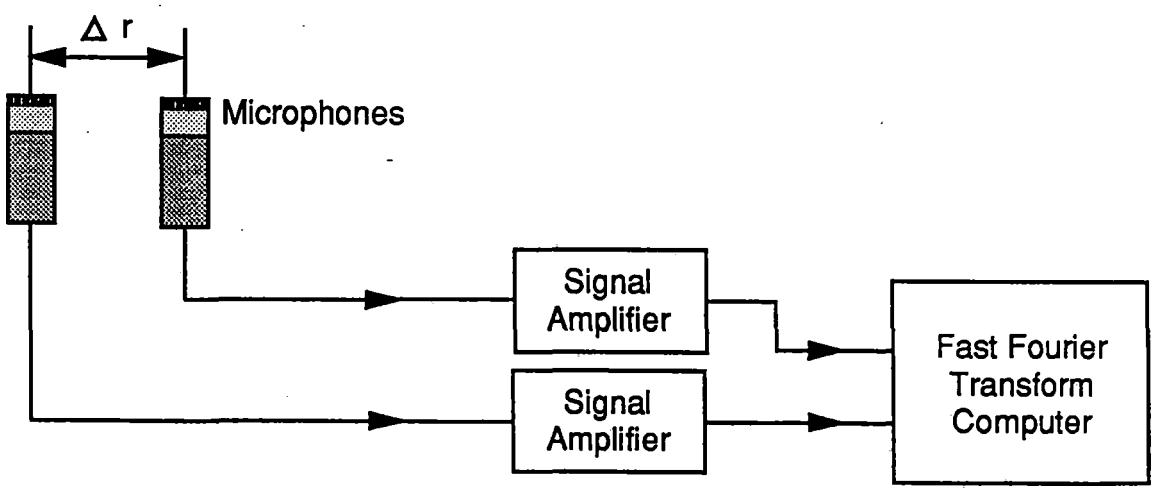

Figure 6. Schematic of Sound Intensity System

2.2 Vibration measurements

An acoustical test facility needs to be well equipped with a vibration measurement capability since sound radiation from vibration of solid structures is an important part of the overall noise problem. Both the guideway and the vehicle body require vibration measurements in order to understand the basic noise generating mechanisms.

A wide variety of vibration measurement techniques are available to the researcher. In general the method is based on a surface mounted transducer that converts motion of the vibrating surface to electrical signals which are amplified and recorded on magnetic tape. After calibration against a standard, the recorded signals are analyzed for overall vibration levels, for frequency band levels, for various motion descriptors (acceleration, velocity or displacement), as required. This section is not intended as a primer on vibration measurement techniques. Summaries of vibration measurement methods can be found in handbooks on acoustical measurements and noise control.[12] A typical measurement system is shown in Figure 7.

Guideway structureborne noise - The guideway has a major effect on the noise radiated from a maglev system at low and medium speeds.[2] Guideways with undamped steel girders are measured to be about 5 dBA noisier than an all-concrete guideway for passbys of maglev vehicles. Despite their propensity for being noisier, steel structures are generally preferred over concrete for reasons of cost or ease of fabrication. A measurement program designed to identify the sources of structureborne noise radiation could result in development of quieter guideways, especially those made of steel. Such a program would involve correlation of noise radiated and the vibration of key components of the structure.

Vibration measurements play a key role in developing noise control from structures since the intensity of sound produced by a vibrating surface is proportional to the mean square velocity of that surface. Measurements of the amplitude and modal pattern of the vibration field together with the mechanical power flow through the structure are fundamental to determining the sources of noise in guideway structures.

Vehicle structure - The vehicle skin vibrates under the fluctuating pressure loading of the turbulent boundary layer at high speed. How much these vibrations contribute to the radiated noise at high speed is unknown. As discussed in Section 1, this is one of the most

pressing of the source questions. If it could be determined whether the structural radiation is significant, then the structural design could be altered accordingly. An experiment combining measurements of vibration, near field sound pressure and wall pressure at the vehicle skin under turbulent boundary layer loading could serve to answer the question.

Such a measurement program might, for example, measure the vibration response of the vehicle skin while at the same time measuring the pressure fluctuations of the boundary layer adjacent to the skin. The vibrations of the panel would be determined by attaching many light weight accelerometers to the interior surface of a panel of the vehicle skin. Data would be analyzed to determine the modal structure of the panel and to correlate the information with the pressure field caused by the turbulent boundary layer outside the panel.

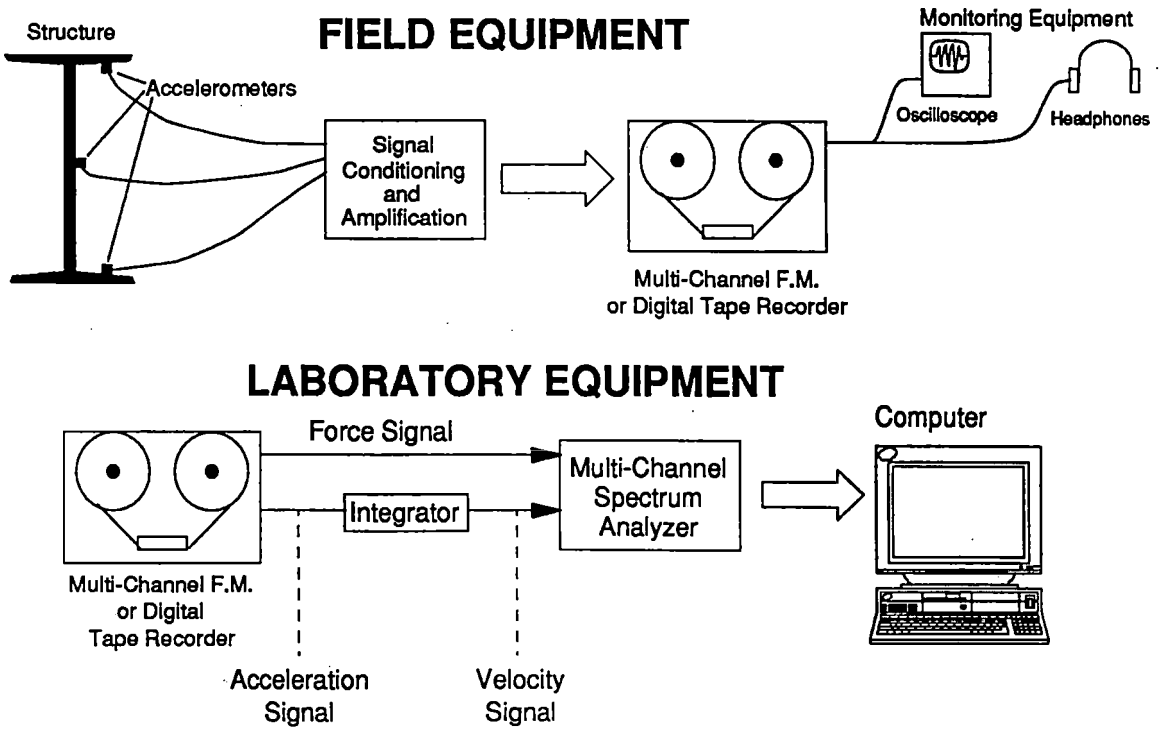

Figure 7. Schematic of Vibration Measurement System

2.3 Recommended Tests to Fill Research Gaps

In Section 1 we listed key noise issues that need to be resolved through an acoustic test program. In Section 2, we describe various noise and vibration measurement methods at the researcher's disposal. This subsection puts the two together in a table as a guideline for a future acoustical test program.

Table 1. Recommended Tests to Resolve Maglev Noise Issues

ISSUES	TEST PROGRAMS
Aeroacoustic sources	Microphone array measurements Microphones mounted on vehicle surface
Interior noise sources	Sound intensity measurements
Vehicle structural radiation	Panel-mounted vibration transducers Microphones mounted on vehicle surface Near-field/far-field microphones
Guideway structural radiation	Sound intensity measurements Vibration power flow measurements
Vehicle/Guideway flow interaction	Scale model flow visualization Microphone array measurements
Noise barrier effectiveness	Multiple-point microphones
Boundary layer control	Scale model wind tunnel tests
Noise from rolling wheels	Scale model noise tests Full scale noise measurements in Japan
Noise from lifting surfaces	Scale model noise/wind tunnel tests
Active cancellation (Interior)	Multiple-point microphones Sound intensity measurements

3. RECOMMENDED ACOUSTICAL TEST FACILITY

An acoustical test facility at the maglev test track will be important to conduct testing during the development stage of prototype vehicles. The size and scope of such a test facility depends on the philosophy of the sponsors of the development program - whether the facility will be a support operation for tests at the test track only, or a center for acoustic research on a wide variety of high speed vehicles. Each of these approaches affects the type of staff and instrumentation for the facility, as well as the budget necessary to continue operations.

3.1 Staff

The staffing requirements depend on how acoustic testing associated with the maglev program will be directed:

- test track's own personnel,
- system developer, or
- outside contractors and research institutions.

Either of the first two approaches requires that the staffing be highly trained, research-oriented professionals in the field of acoustics and capable of conducting independent research and noise control developments. The facility would thus become an acoustic research center for control of noise and vibration from high speed vehicles. The third approach would also require highly trained staff, but since the ideas for fundamental research would come from outside the facility, the staff would take on a support function, such as technicians and data analysts.

Research Facility - A complete research facility concentrating on aeroacoustics would require a major investment and ongoing commitment on the part of funding agencies. In order to justify the investment, there needs to be a demonstrated necessity that the problem is of continuing national importance. Although it is beyond the scope of this report to demonstrate a national need beyond the maglev development program, there is at present no coordinated research program in aeroacoustics of surface vehicles. There is a need for a focus point for such research and locating a research facility at the maglev test track could provide that focus.

For the case of a minor research facility, the staffing would be made up of highly qualified professionals in the field of acoustics and noise control engineering, together with a support staff of technicians and analysts to conduct measurement programs, analyze the data and prepare test reports. Staff size depends on the extent of the funding and the scope of the program, but at a minimum the facility would need the following:

- Director - an internationally known and experienced research professional, with a Ph.D. and experience in both industry and academia,

- Acoustical Professionals - two or more acoustical engineers with advanced degrees, capable of conducting independent research programs and preparing and publishing technical research papers,

- Technicians and Analysts - two or more technicians capable of conducting complex field measurement programs, instrument maintenance and record keeping, and one or more computer specialists with training in data analysis and programming,

- Administration - one executive secretary, one part-time word processor and one part-time librarian.

Support Operation - In the alternative that the test track operations would be offered as a facility for use by outside contractors and the developers of maglev vehicles, then the acoustical test facility would require a lesser staffing requirement. As a support facility, the staff would conduct measurements and analyze data in response to direction from outside contractors. Interpretation of the data and supervision of the data acquisition would be done by the professional staff of the sponsoring agency. Consequently, the staff could consist of the following:

- Facility coordinator - an acoustical professional with extensive background in noise control engineering and experimental testing procedures,

- Technicians and Analysts - two or more technicians capable of conducting complex field measurement programs, instrument maintenance and record keeping, and one computer specialist with training in data analysis and programming,

- Administration - one secretary and one part-time librarian.

3.2 Physical layout

The location of a maglev acoustic test facility in either case should be near the test track for easy access. At TransRapid's Emsland test track in Germany the acoustic laboratory is in the maintenance building in which the maglev vehicles are serviced. In that facility, laboratory set-up, equipment maintenance and storage and data reduction facilities are all located in a rather cramped space of 8 meters by 12 meters (estimated from observation). Space for an instrumented van is provided in the adjacent service bay shared with the maglev vehicle. Computer facilities are located in a separate building.

A good layout for an acoustical laboratory should include offices, computer peripherals, laboratory set-up, data reduction, equipment storage, document storage, and garage for instrumented van all in adjacent spaces to facilitate communication. The space needed for the entire facility depends on the scope of the activity, discussed above, but the minimum space needed is as follows:

• Offices - Director	3.5m x 4.5m
Staff	3.0m x 4.0m (each office)
Technician	3.5m x 4.5m (shared by two)
• Computer peripherals	3.0m x 4.0m
• Data reduction	3.5m x 4.5m
• Equipment set-up	5.0m x 8.0m
• Equipment maintenance and storage	3.5m x 4.5m
• Garage and loading area for van	4.5m x 10.0m

Total minimum space for a complete research laboratory, assuming two offices each for staff and technicians, is just under 200 square meters, not including amenities and common area. The reduced scale support facility discussed above would require about 175 square meters of working space.

3.3 Equipment

The equipment roster for a well-equipped acoustic test facility would be nearly identical for either type of mission, research facility or test support facility. Equipment would be required for:

- Noise measurements - sound level meters, microphones, calibrators, preamplifiers, supporting stands, cable, connectors, arrays, sound intensity equipment;

- Vibration measurements - accelerometers, calibrators, amplifiers, integrators, cables, connectors;

- Data acquisition and analysis - multi-channel digital audio tape recorders, analog-to-digital converters, frequency analyzers, filters, portable computers;

- Computer facilities - desk top computers with network, work station with access to main frame, laser printer, plotter, graphics work station;

- Instrumented van - high step van body, custom fitted work space, racks for instruments, built-in power supply for instruments, auxiliary heat, remote radio and telephone transmitter.

REFERENCES

1. U.S. Congress, Office of Technology Assessment, "New Ways: Tiltrotor Aircraft & Magnetically Levitated Vehicles," OTA-SET-507 (Washington, DC: U.S. Government Printing Office, October 1991).

2. Hanson, Carl E., Philip Abbot and Ira Dyer. "Noise Sources of High Speed Maglev Trains," Task Report, BAA 191, Federal Railroad Administration, Washington, D.C., May 1992.

3. Hanson, C.E. "Noise Criteria for High Speed Maglev Trains," Task Report HMMH-291550-2, BAA 191, Federal Railroad Administration, Washington, DC, September 1992.

4. Alscher, Hans. "Aero-Acoustic Investigations of the Magnetic Train TRANSRAPID 06," Proceedings of Magnetically Levitated Systems and Linear Drives, The Institute of Electrical Engineers of Japan, Yokohama, Japan, July 1989.

5. Crighton, David G. "Airframe Noise," Chapter 7 in Aeroacoustics of Flight Vehicles: Theory and Practice, NASA Reference Publication 1258, Vol. 1, WRDC Technical Report 90-3052, (Harvey H. Hubbard, ed.), NASA Langley Research Center, Hampton, Virginia, August 1991.

6. Blake, W.K. Mechanics of Flow-Induced Sound and Vibration, Vol II, Ch.9, Academic Press, Inc., Orlando, FL, 1986.

7. Barsikow, B., W.F.King III, and E. Pfizenmaier. "Wheel/rail Noise Generated by a High-speed Train Investigated with a Line Array of Microphones," J.Sound and Vibration (1987) **118**, 337-342.

8. Torii, A., et al. "Shinkansen's Sound Source Measurements Using Microphone Array," Proceedings of InterNoise 92, Institute of Noise Control Engineering, Toronto, Canada, 1992, pp. 1171 - 1174.

9. King, W.F. and H.J. Lettman, "On Locating and Identifying Sound Sources Generated by the German ICE Train at Speeds Up to 300 Km/hr," Proceedings of InterNoise 88, Institute of Noise Control Engineering, Avignon, France, 1988, pp. 1391 - 1396.

10. Takano, Y. "Development of 2-Dimensional Microphone Array Measurement System for Noise Sources of Fast Moving Vehicles," Proceedings of InterNoise 92, Institute of Noise Control Engineering, Toronto, Canada, 1992, pp. 1175 - 1178.

11. Crocker, M.J., "Measurement of Sound Intensity," Ch. 14, Handbook of Acoustical Measurements and Noise Control, Third Edition, Cyril M. Harris (ed.), McGraw-Hill, New York, 1991.

12. Harris, Cyril M. (ed.) Handbook of Acoustical Measurements and Noise Control, Third Edition, McGraw-Hill, New York, 1991.