11 - Advanced Systems

NOISE SOURCES OF HIGH SPEED MAGLEV TRAINS

HMMH Report No. 291550-1

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Prepared for:

Federal Railroad Administration
400 7th Street, SW
Washington, DC 20590

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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.

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

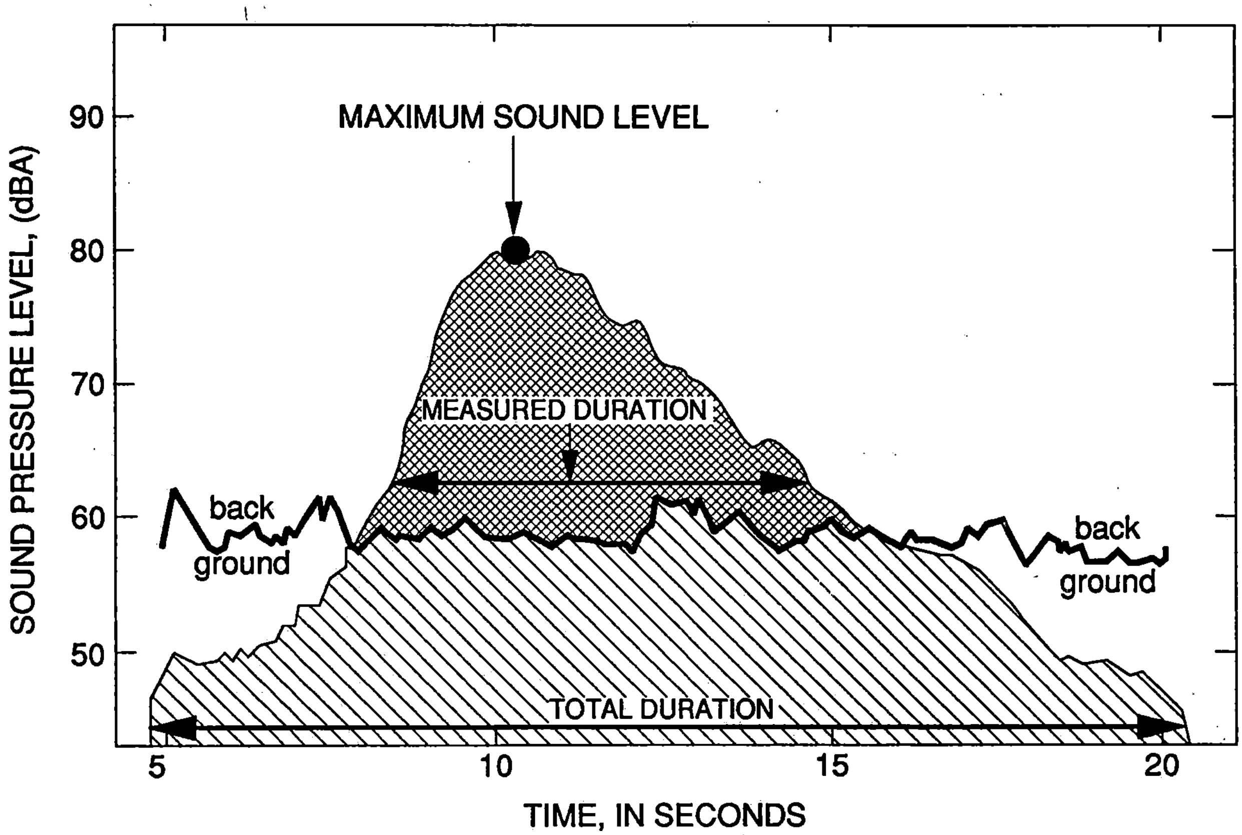

Figure 1. Typical Noise Time History of a Vehicle Passby

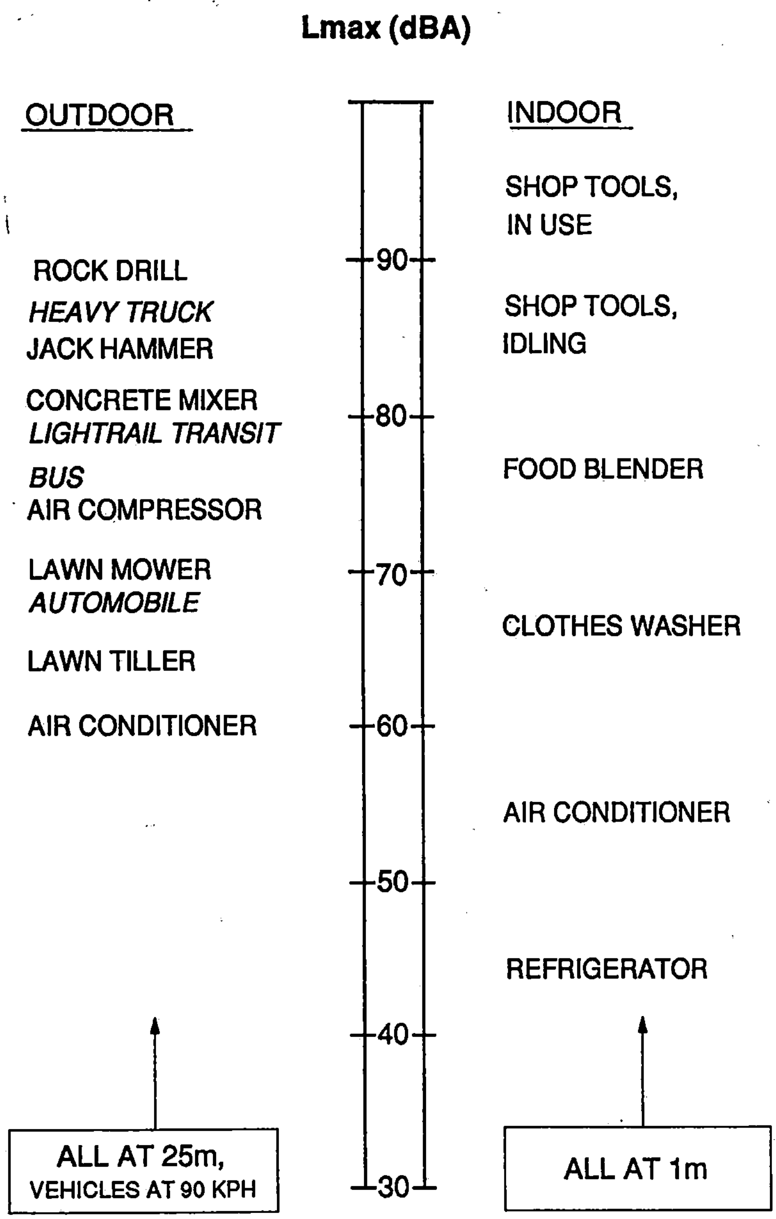

Figure 2. Commonly Experienced Noise Levels

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.

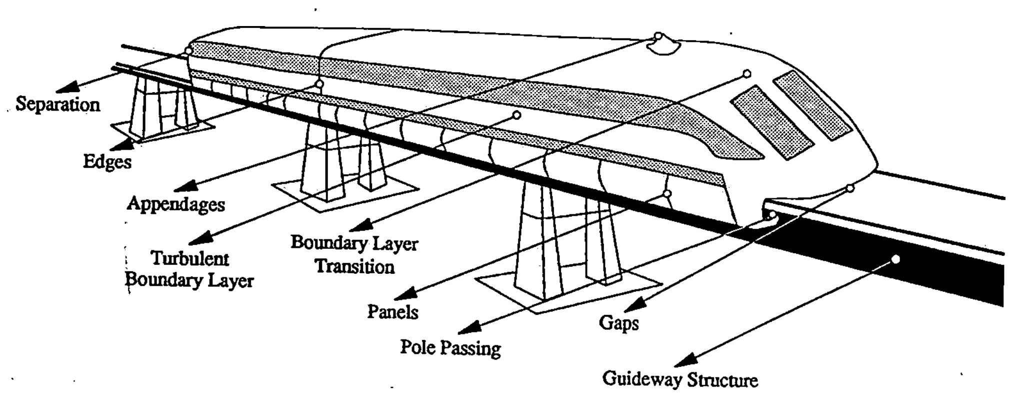

Figure 3a. Noise Sources on an Electromagnetic Maglev System

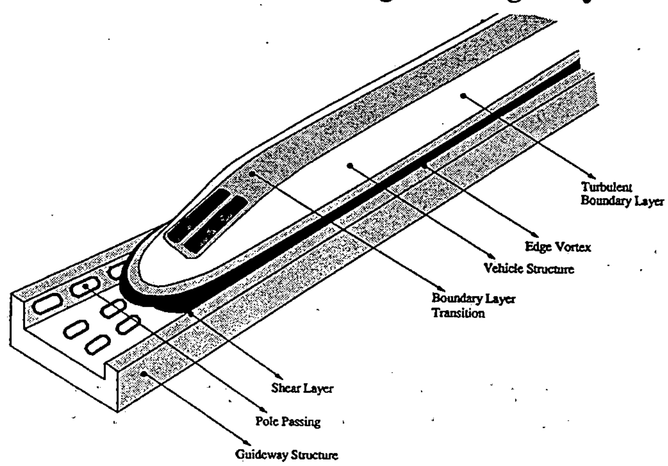

Figure 3b. Noise Sources on an Electrodynamic Maglev System

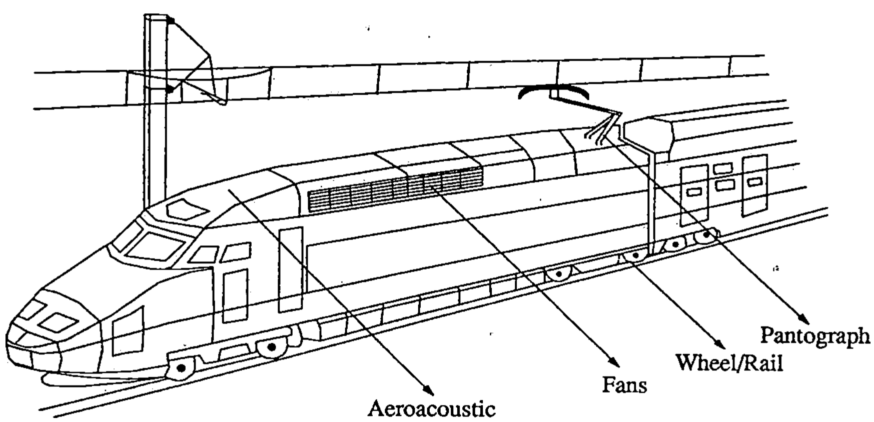

Figure 3c. Noise Sources on a Conventional High Speed Train

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.

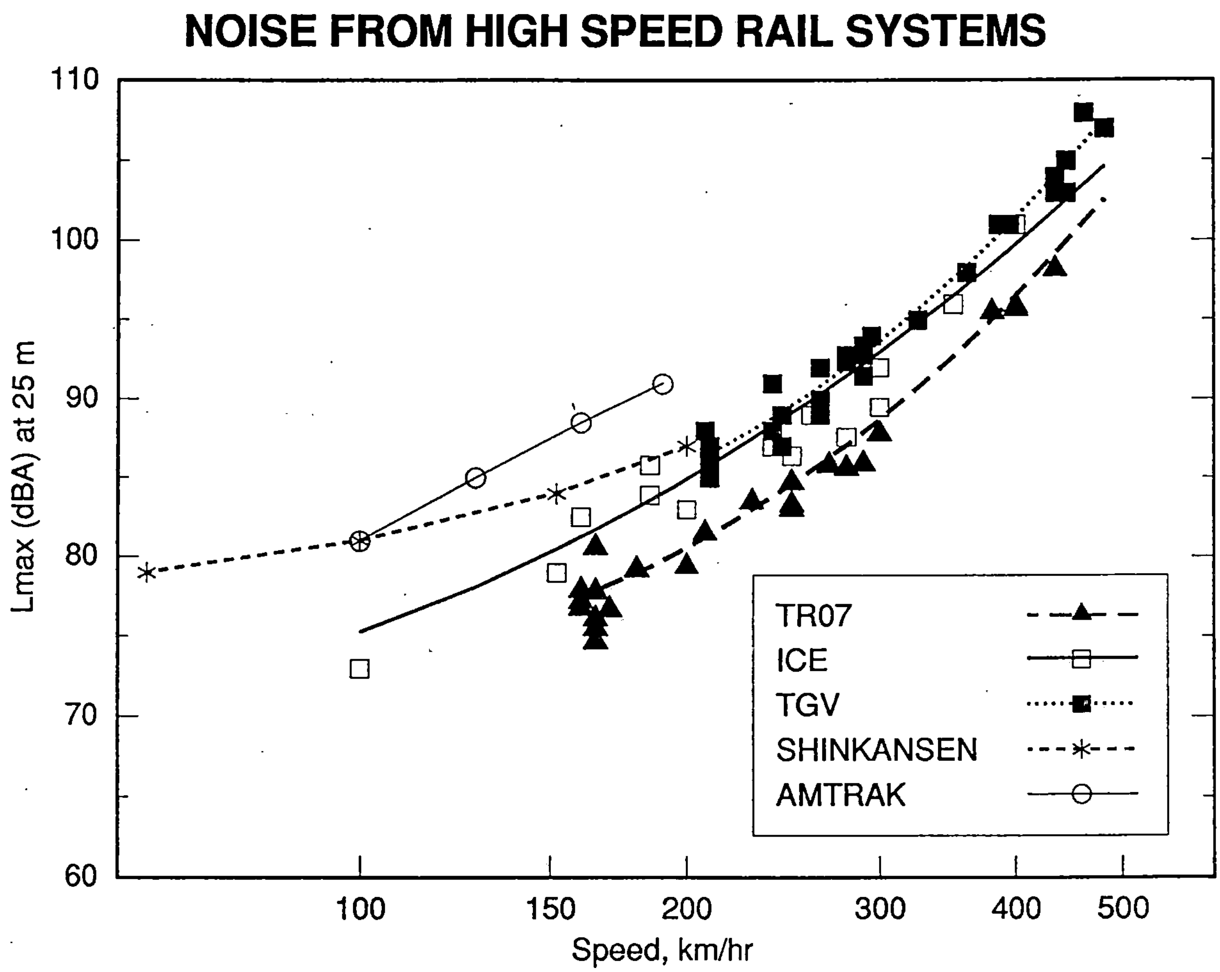

Figure 4. Noise from Maglev and Electrically Powered High Speed Rail Systems

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.

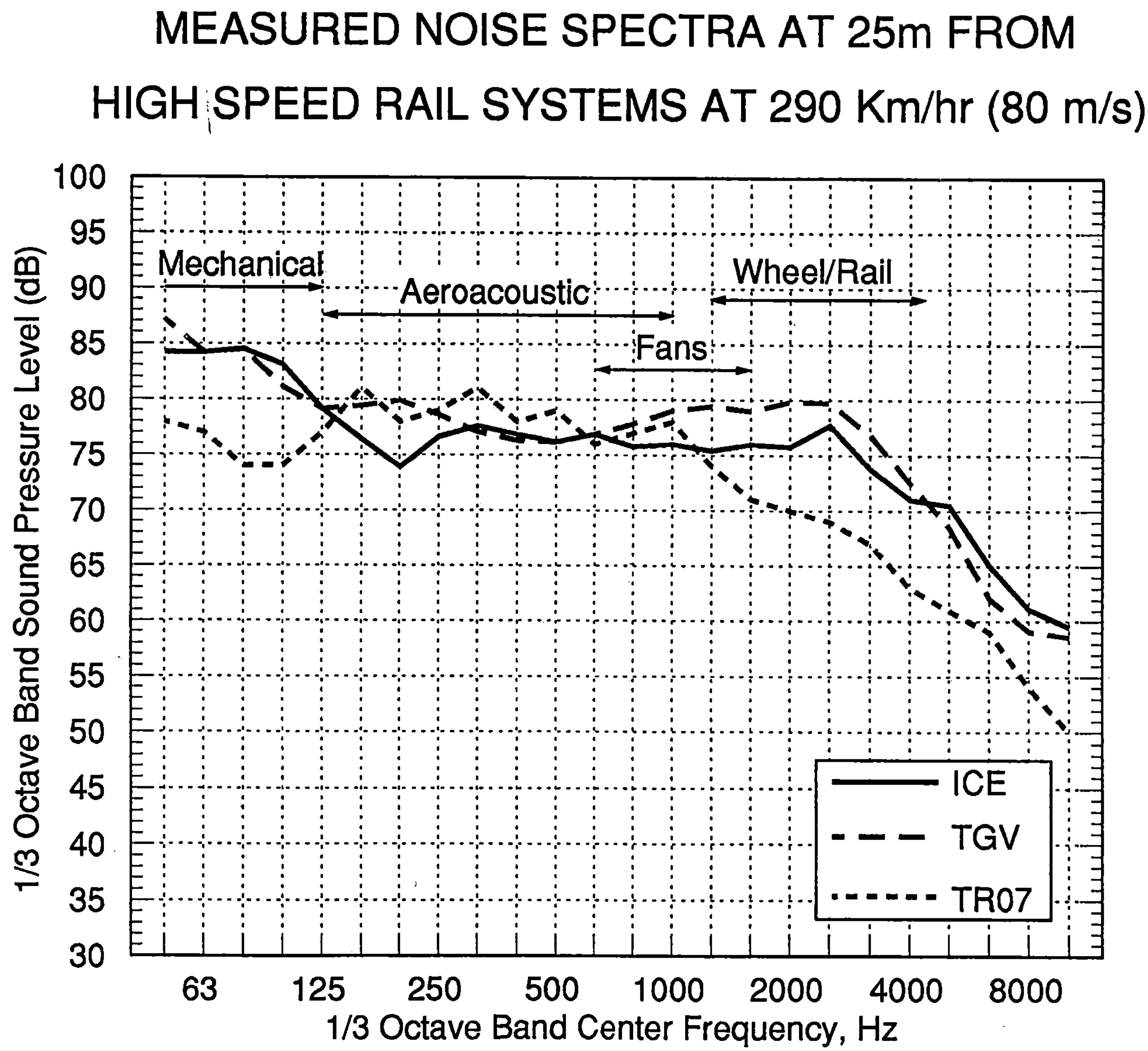

Figure 5. Noise Spectra from Maglev and High Speed Rail Systems at 290 Km/hr (Ref.2)

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.

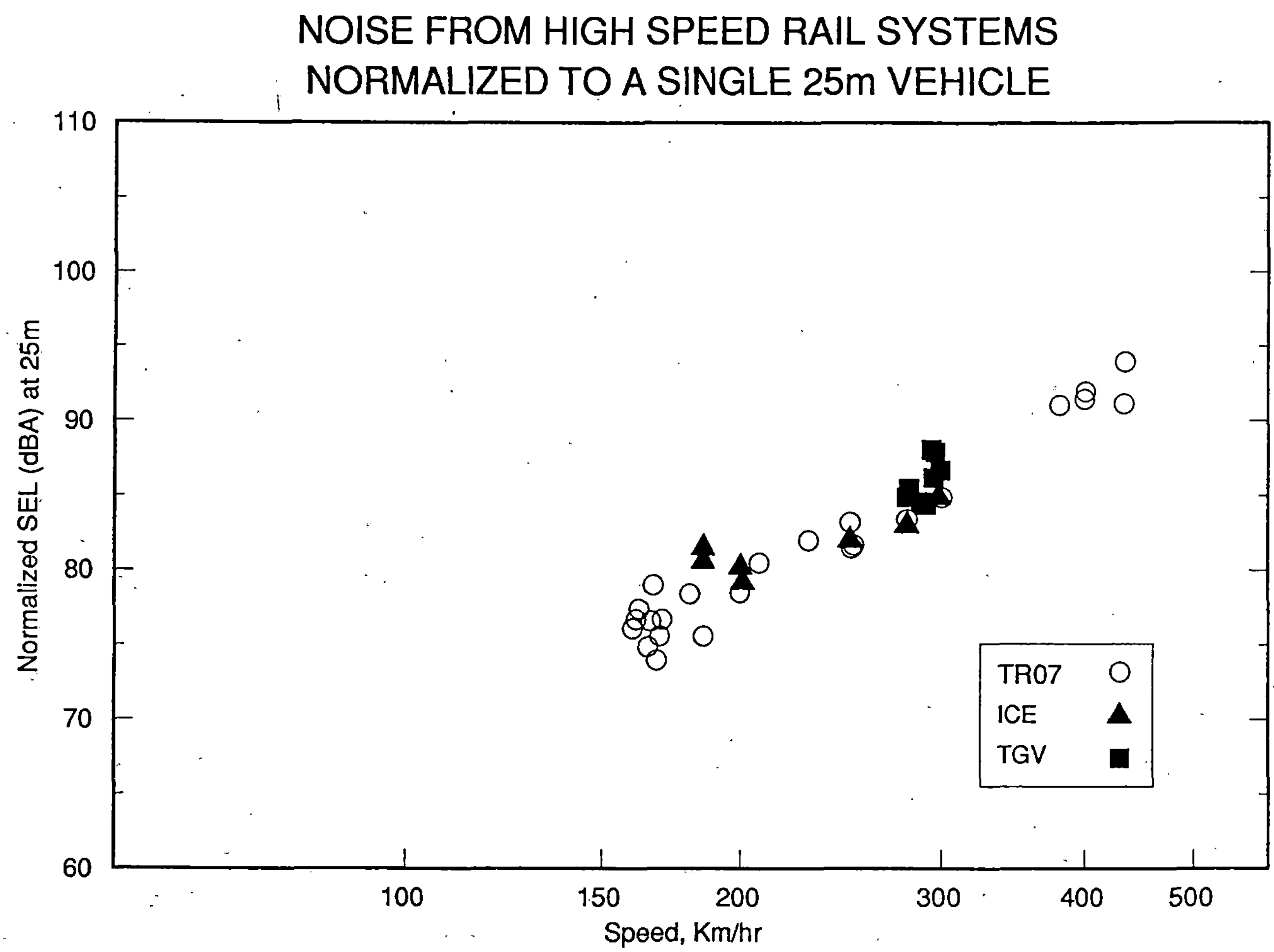

Figure 6. Sound Exposure Levels Normalized to Single 25m Vehicles

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

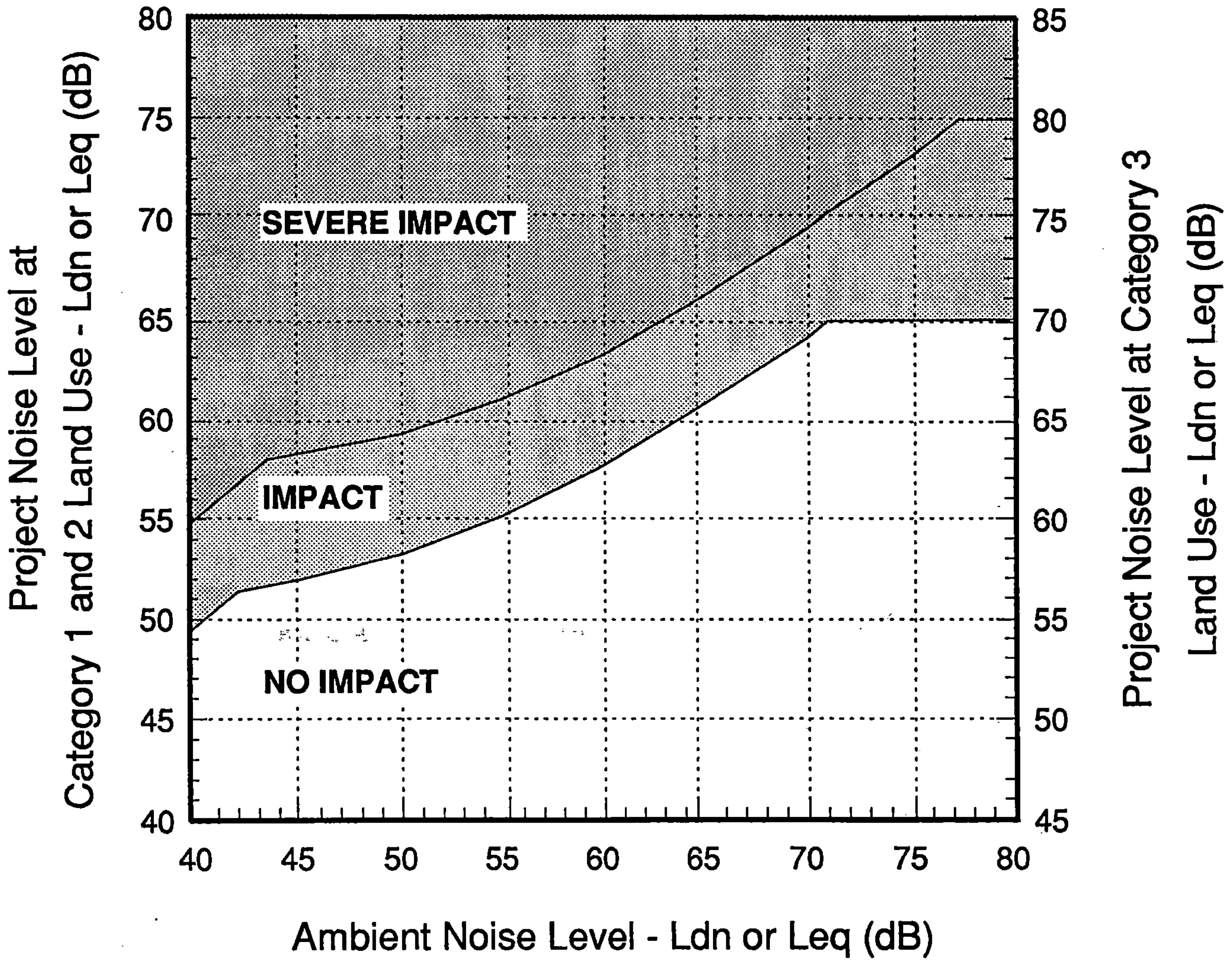

Figure 7. Proposed UMTA Noise Impact Criteria (Ref.6)

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.

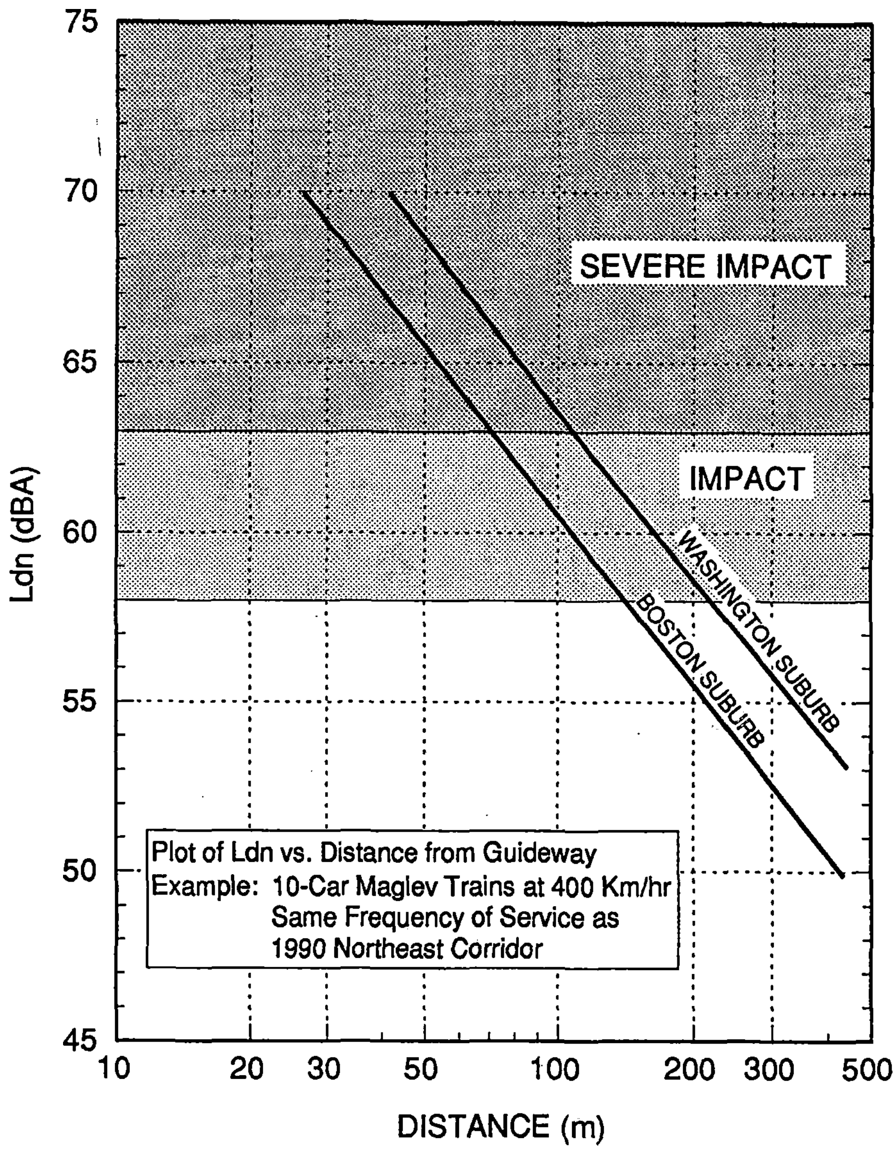

Figure 8. Ldn vs. Distance for Examples

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.

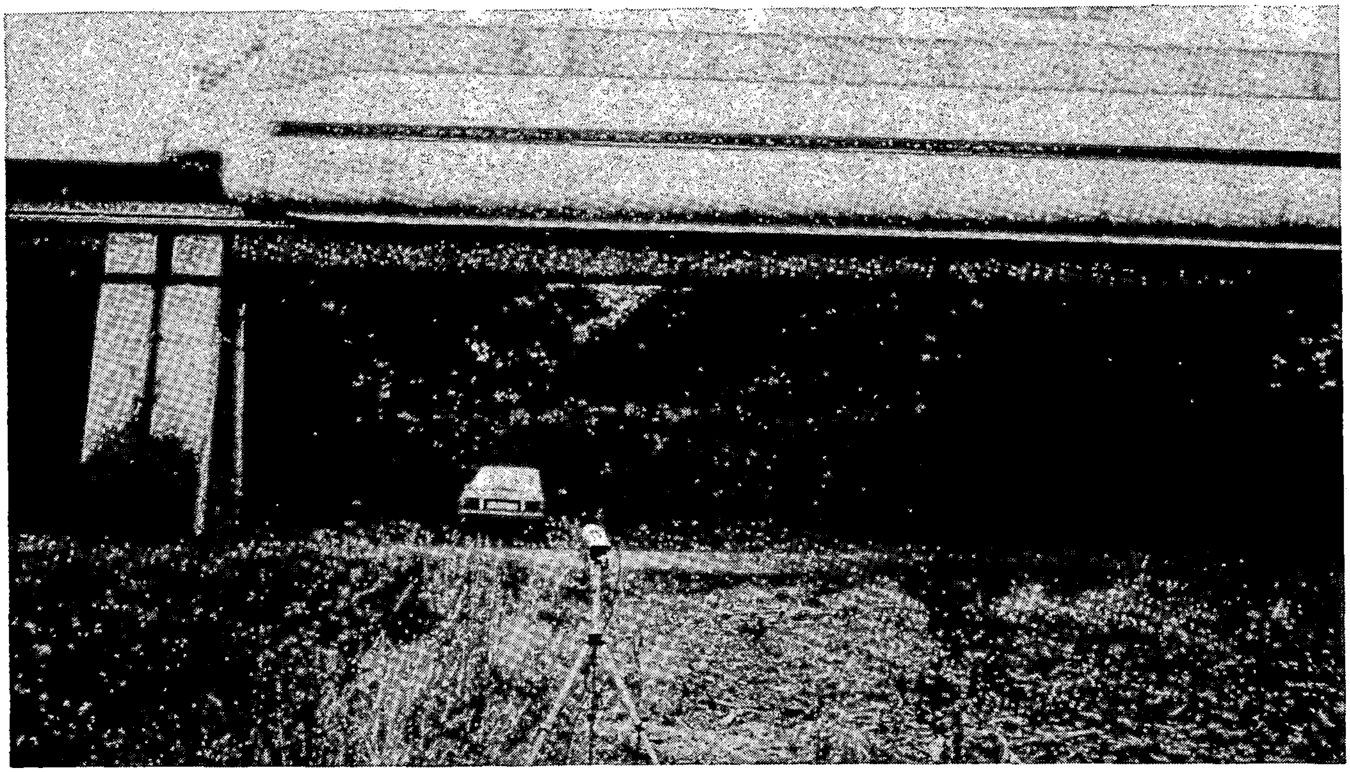

Figure 9. Single Point Noise Measurement of TR 07 at Emsland Test Track

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:

Lmax = 80 + 37 log (speed/200), dBA for speed < 250 Km/hr (69 m/sec), and

Lmax = 83 + 62 log (speed/250), dBA for speed > 250 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.

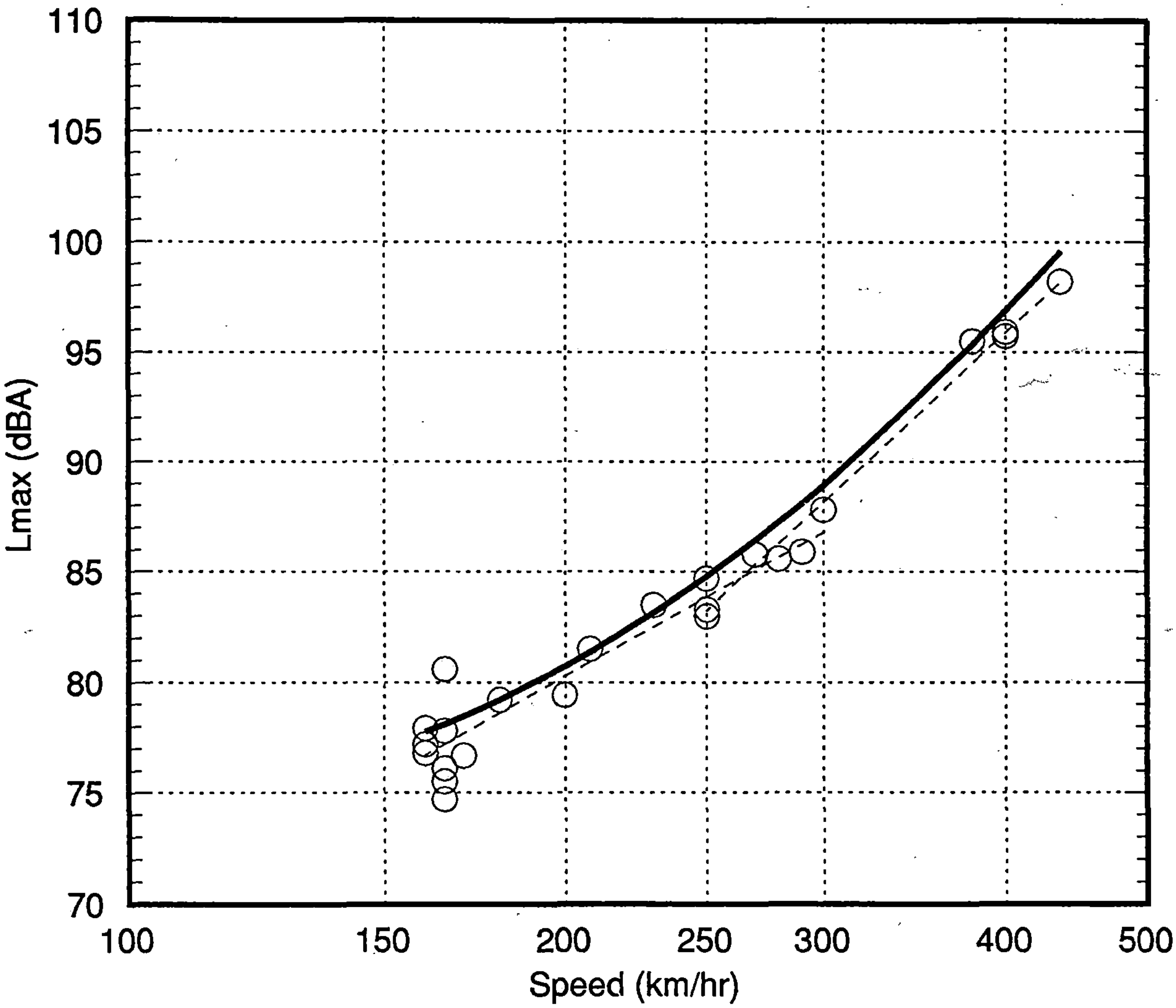

Figure 10. Lmax vs. Speed for TR 07 at 25 meters

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.

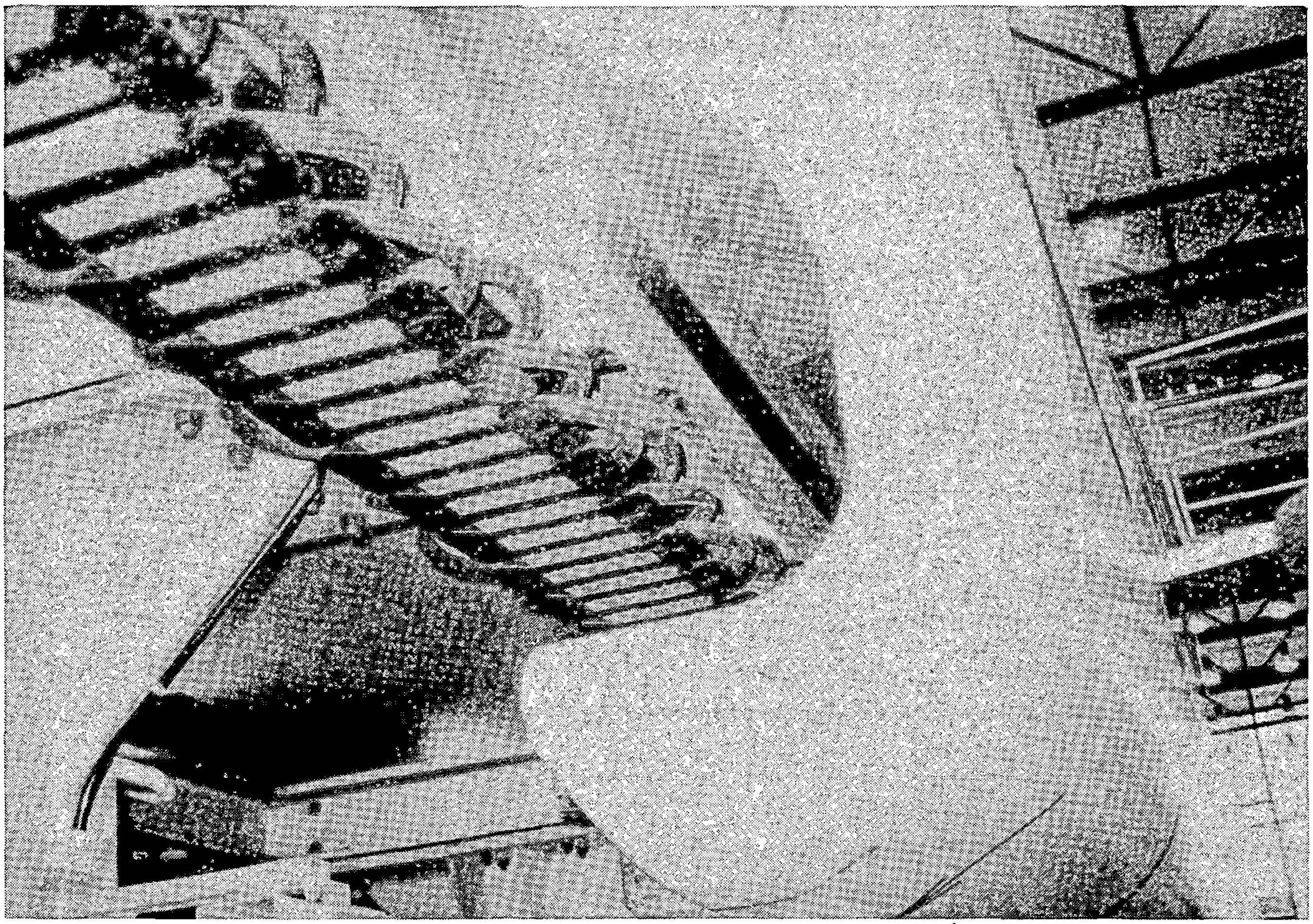

Figure 11. Underside of TR 07 Guideway Showing Magnets

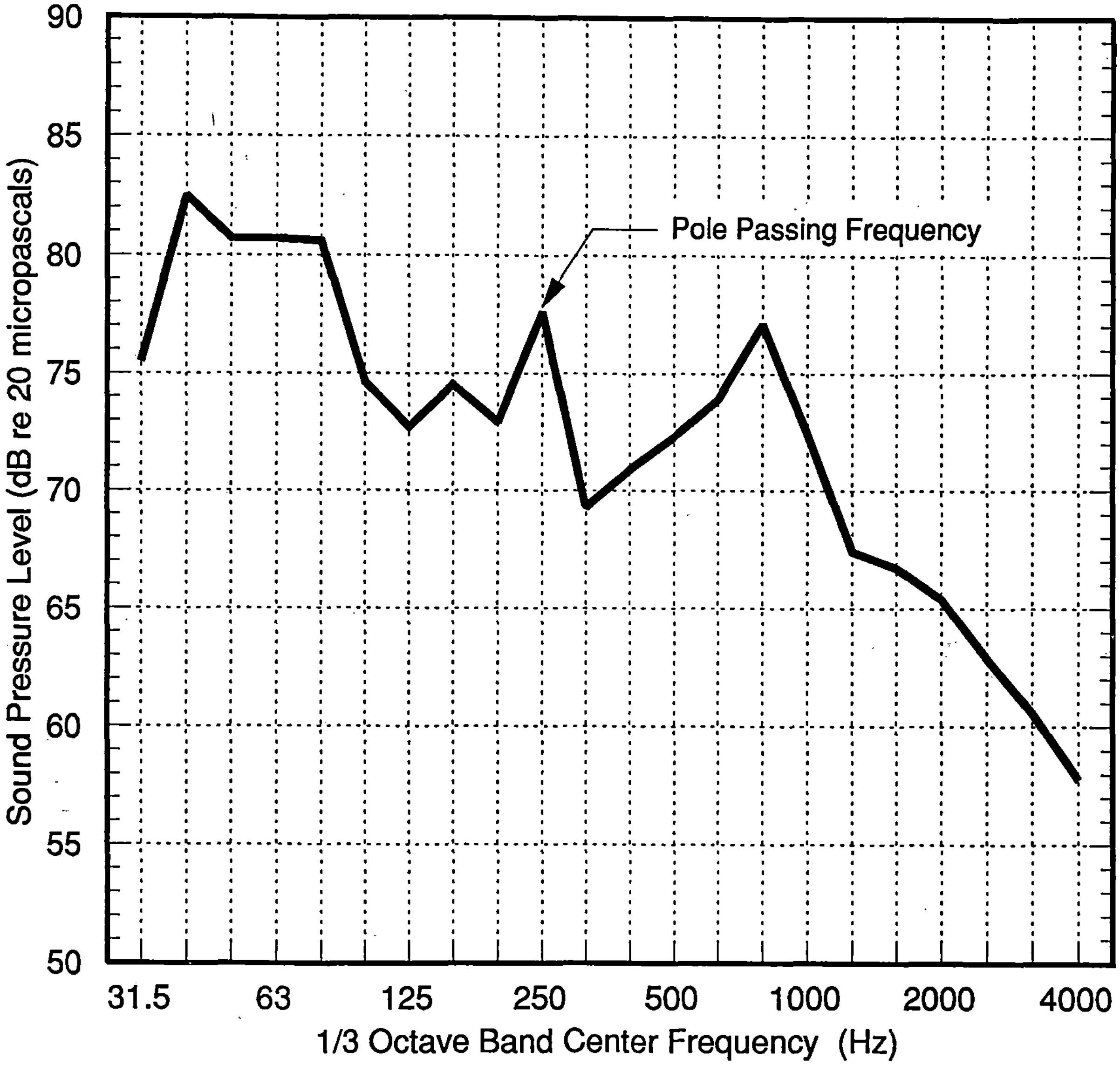

Figure 12. TR 07 Noise Spectrum at 245 Km/hr, 25 m Distance (HMMH data)

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.

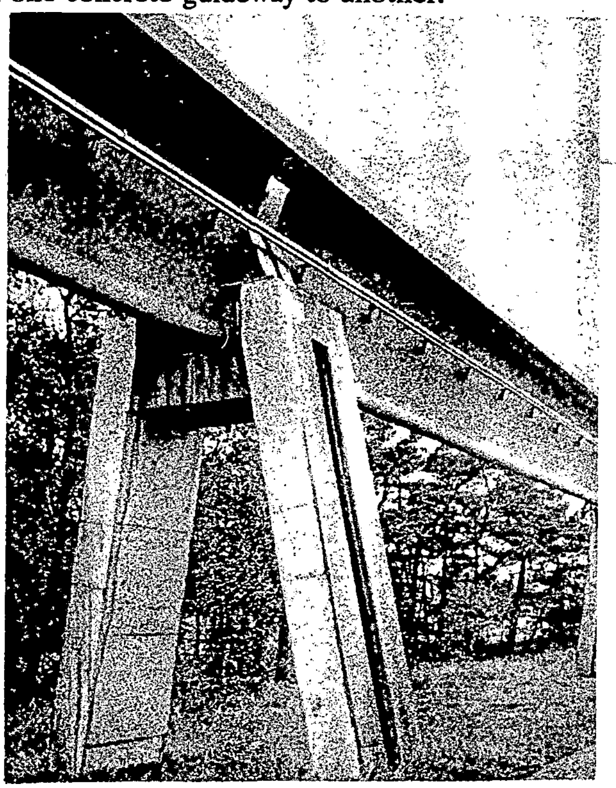

Figure 13. Photograph of Steel Guideway at Emsland Test Track, Germany

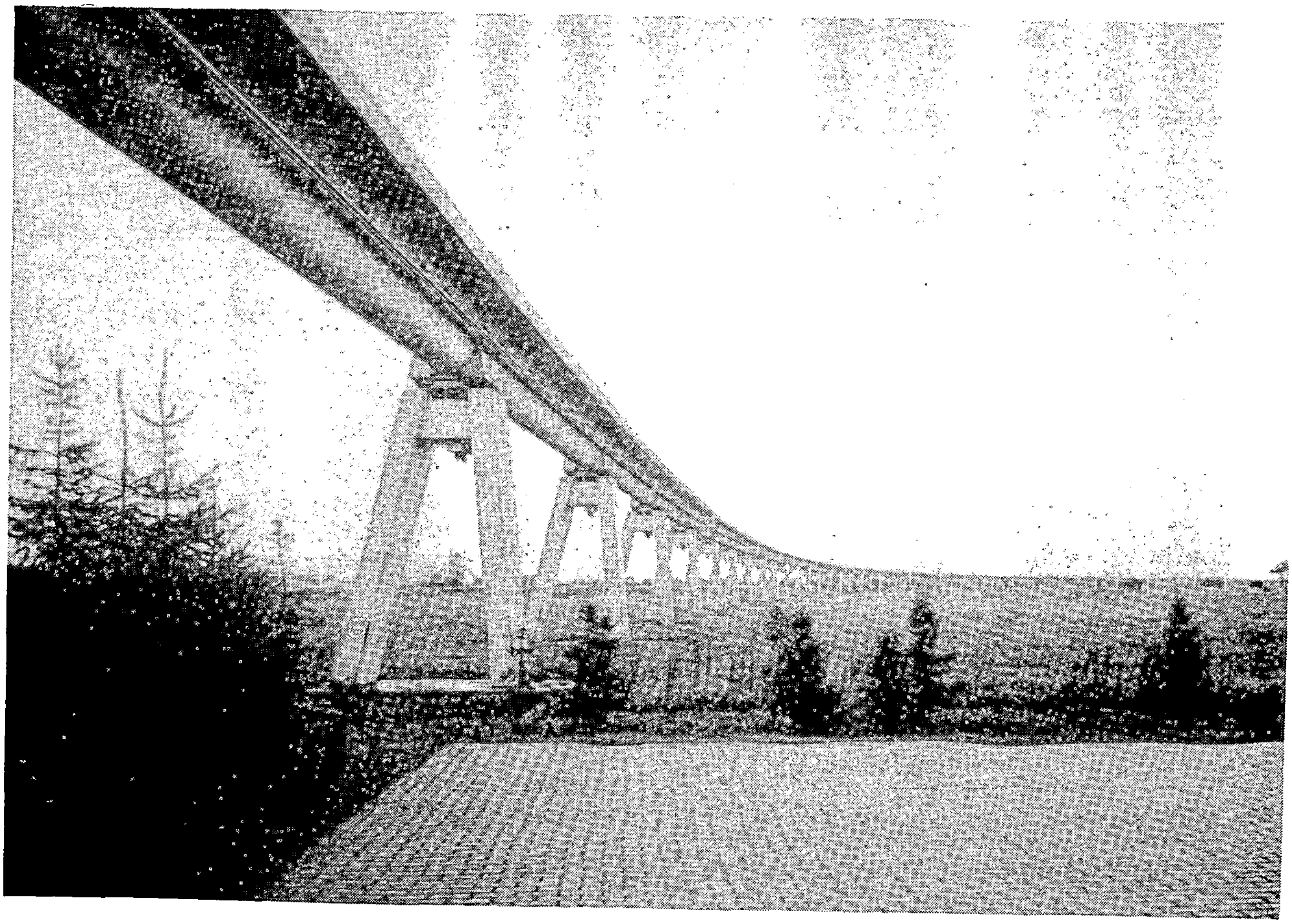

Figure 14. Photograph of Concrete Guideway at Emsland Test Track, Germany

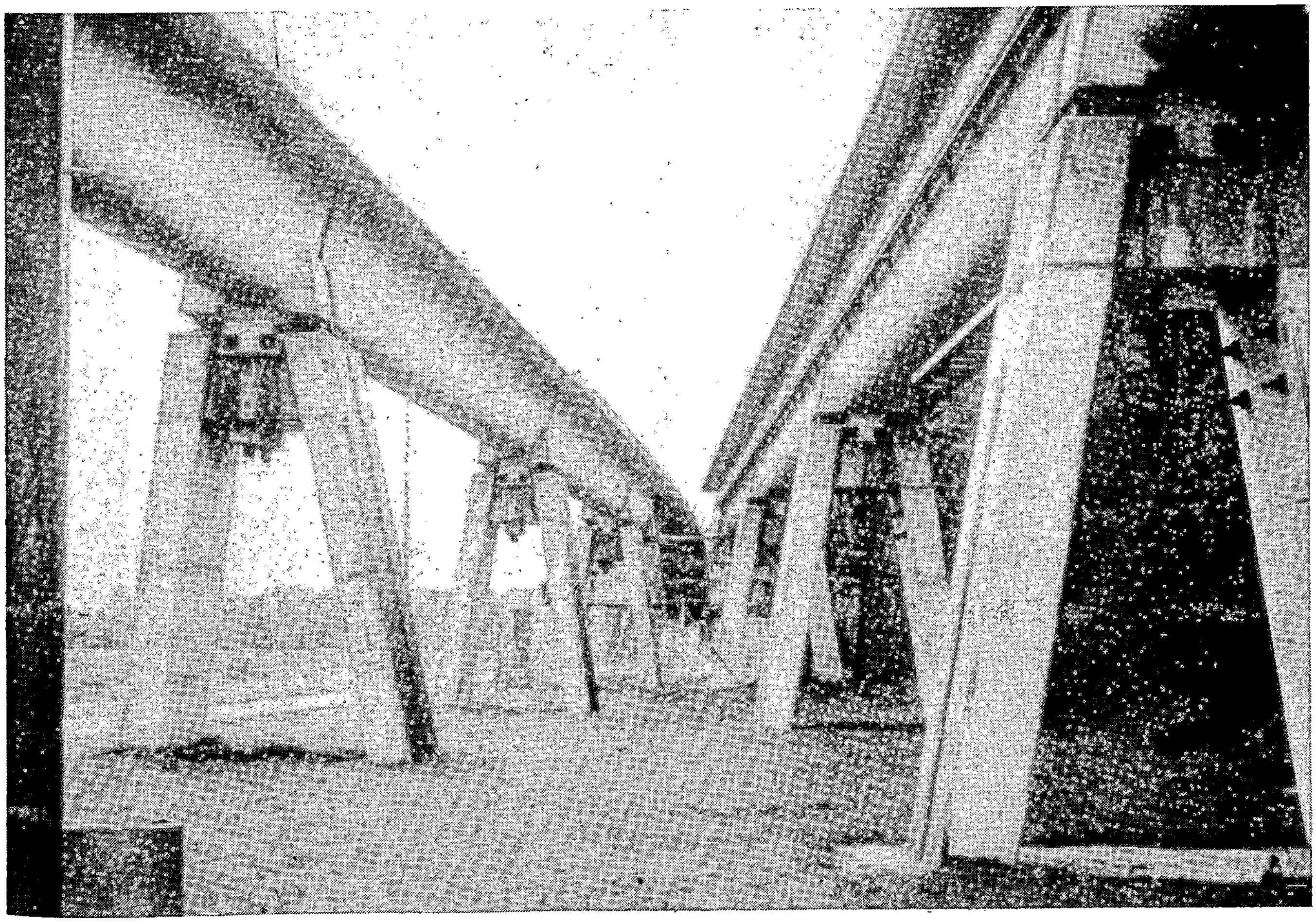

Figure 15. Photograph of Switch at Emsland Test Track, Germany

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,

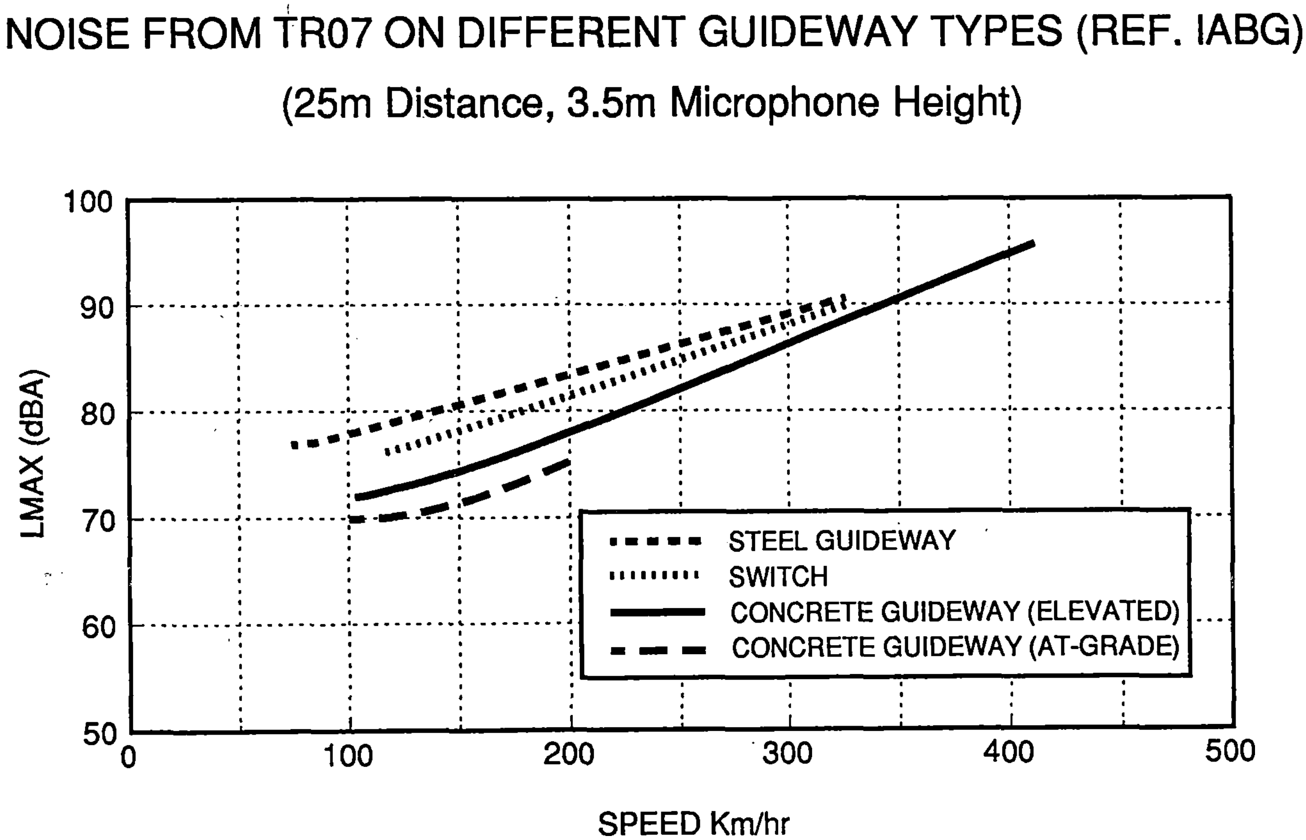

Figure 16. Noise from TR 07 on Different Guideway Types

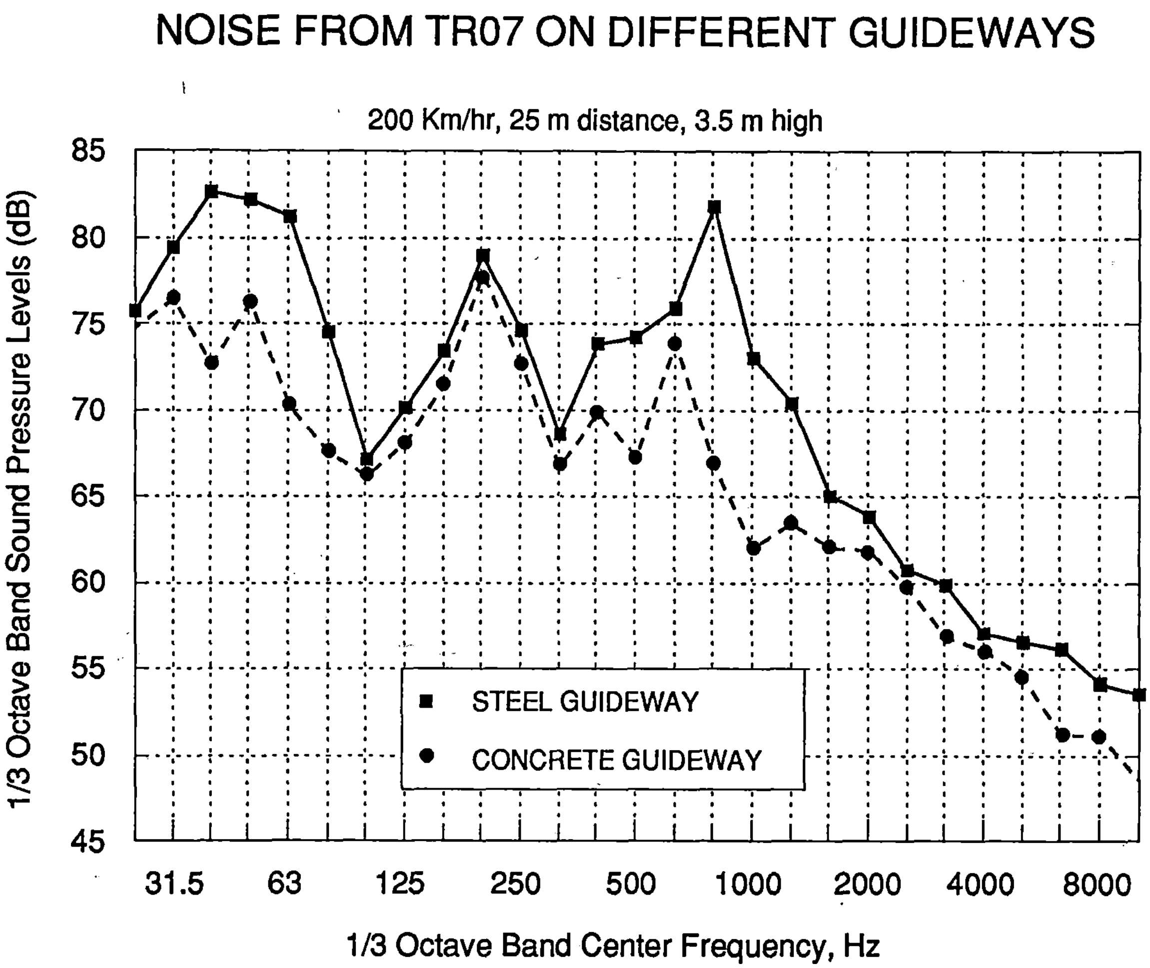

Figure 17. Noise Spectra of TR 07 on Different Guideways

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.

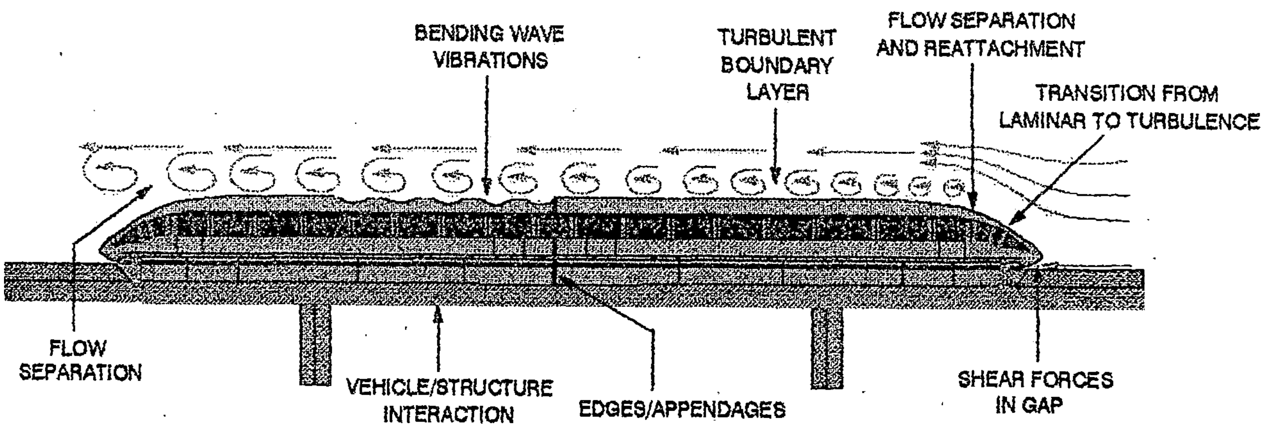

Figure 18. Aeroacoustic Sources on a Maglev System

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.

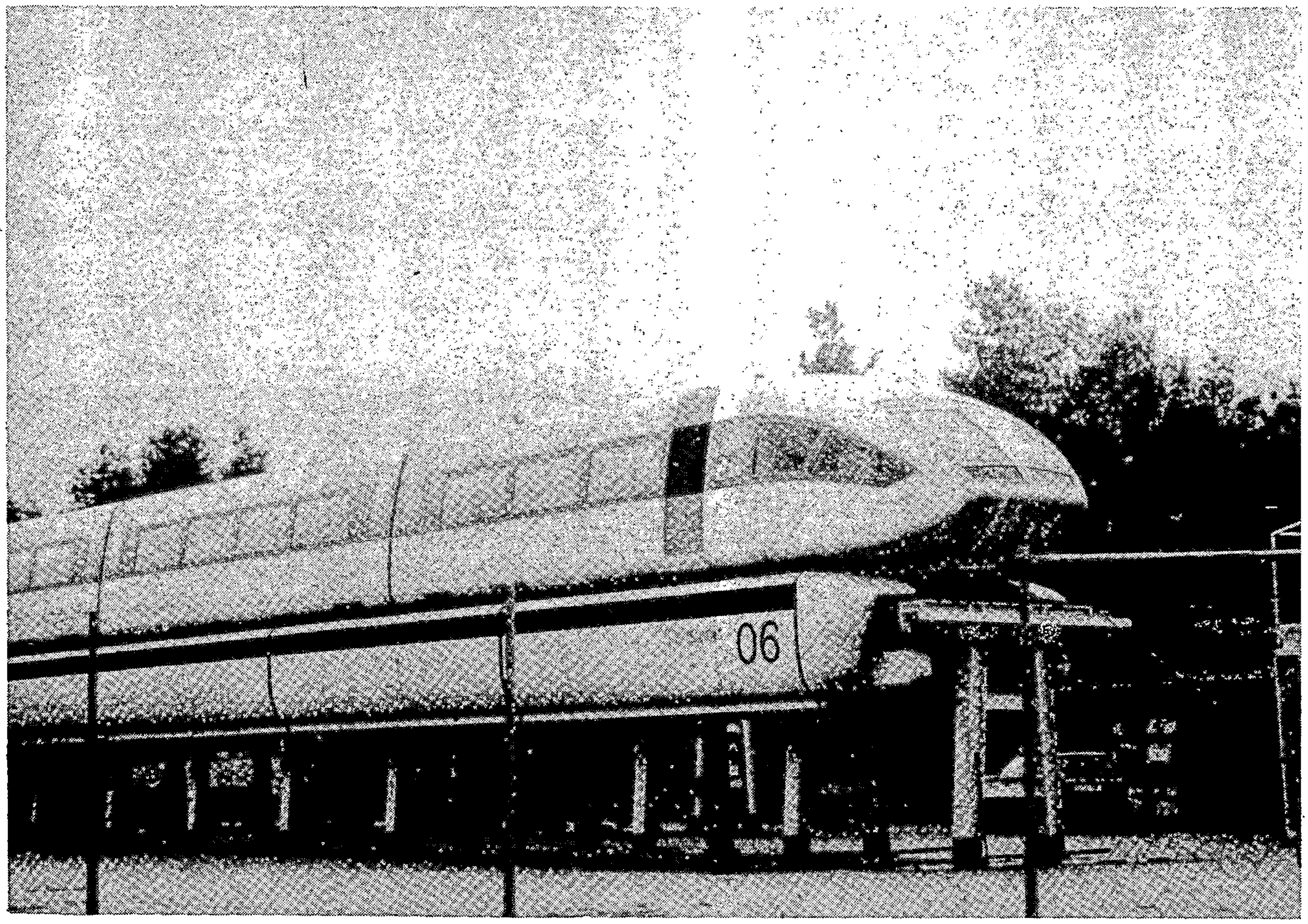

Figure 19. Photograph of Nose of TR 06

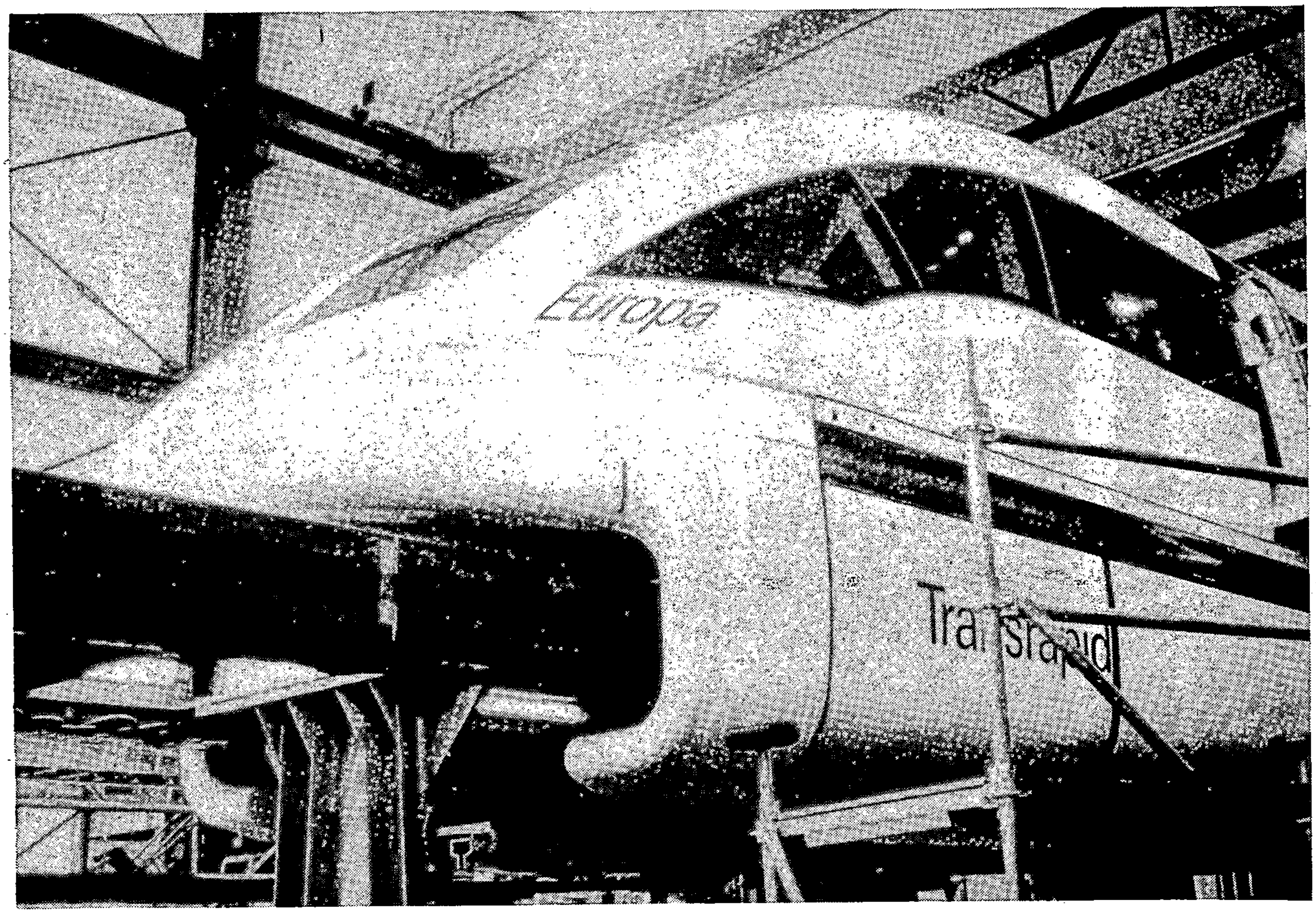

Figure 20. Photograph of Nose of TR 07

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 $f_c \sim U/\delta^*$.

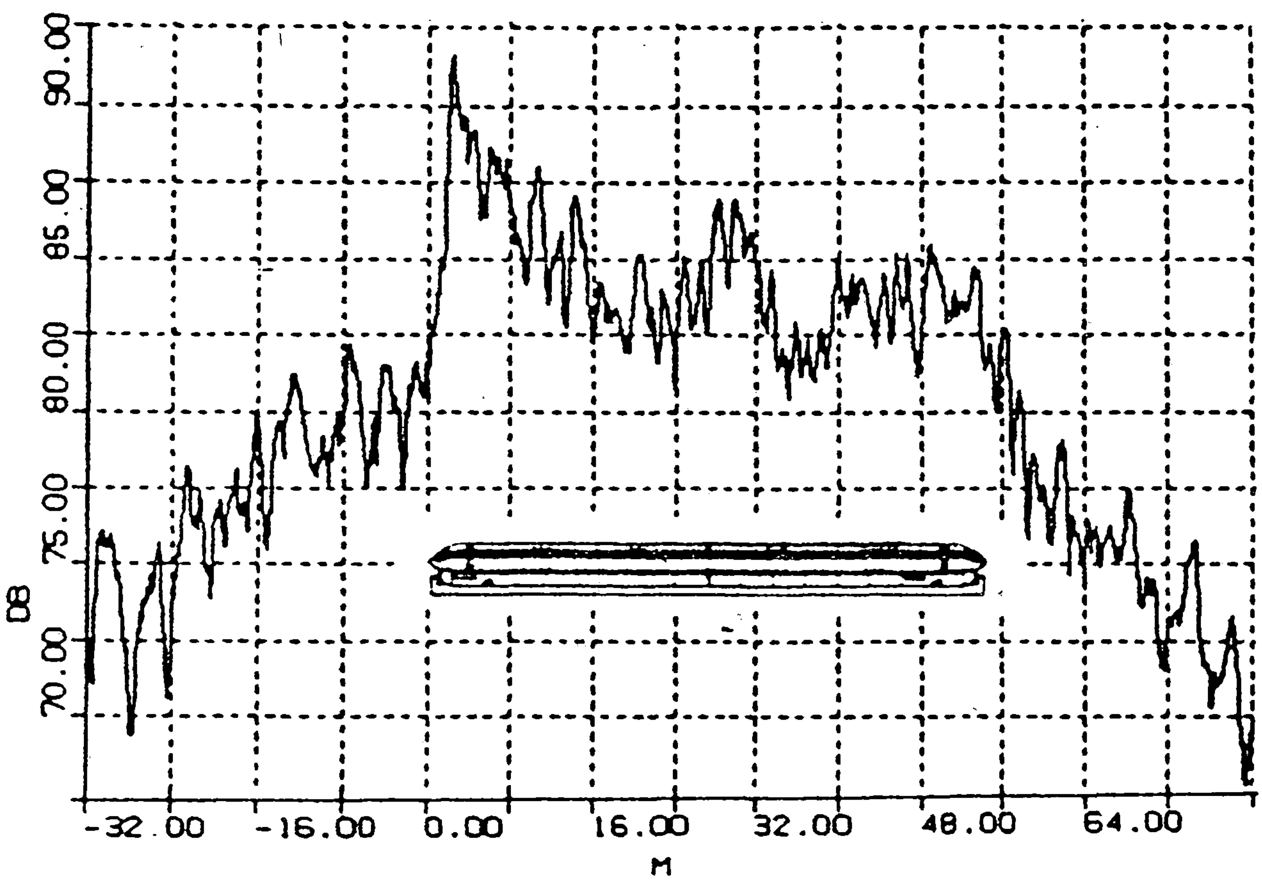

Figure 21. Longitudinal Noise Profile of TR 06 at 108 m/sec (from Ref. 12)

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.

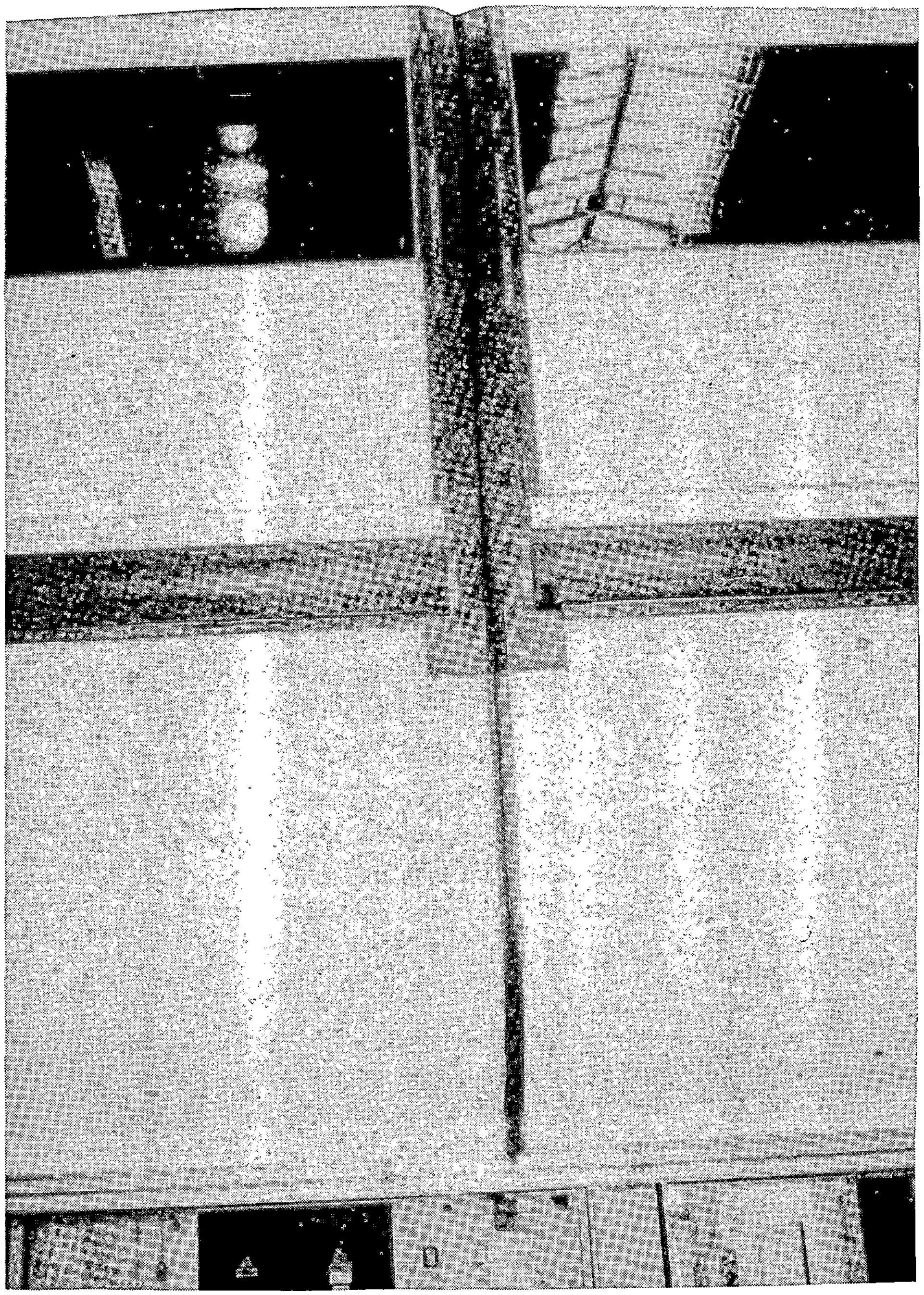

Figure 22. Photo of Joint between Two Vehicles

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.

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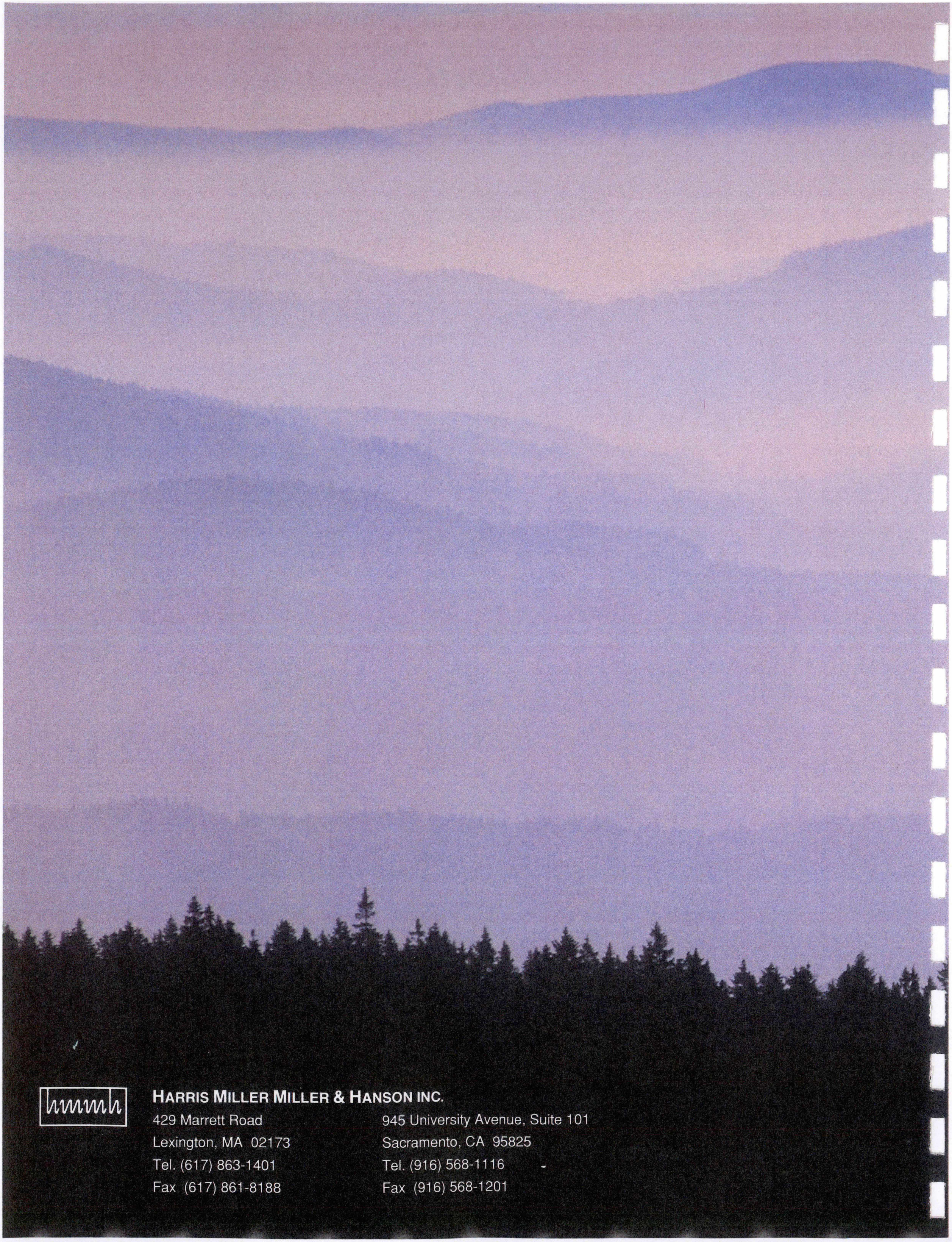

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