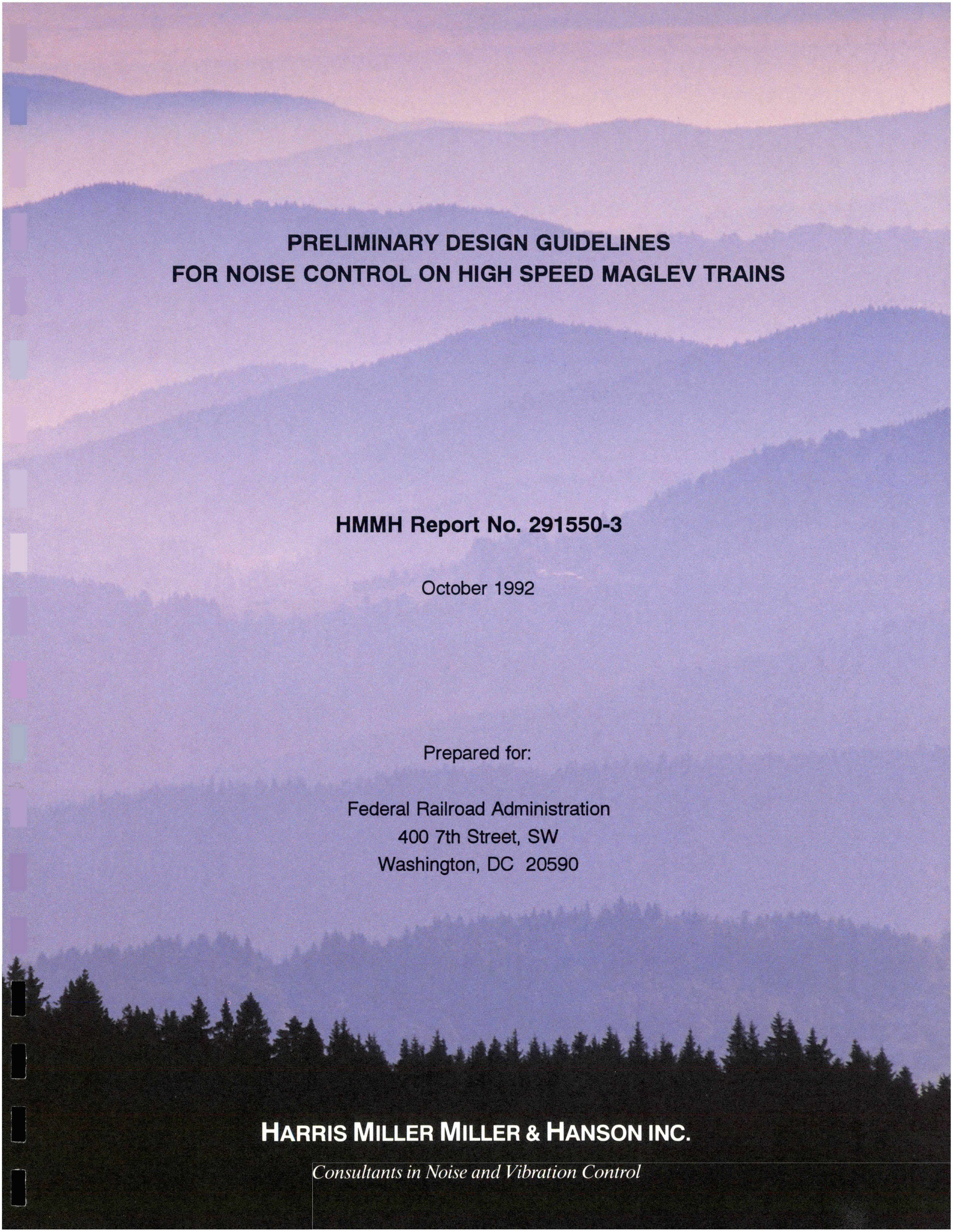
11 - Advanced Systems



PRELIMINARY DESIGN GUIDELINES FOR NOISE CONTROL ON HIGH SPEED MAGLEV TRAINS

HMMH Report No. 291550-3

October 1992

Prepared for:

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

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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.

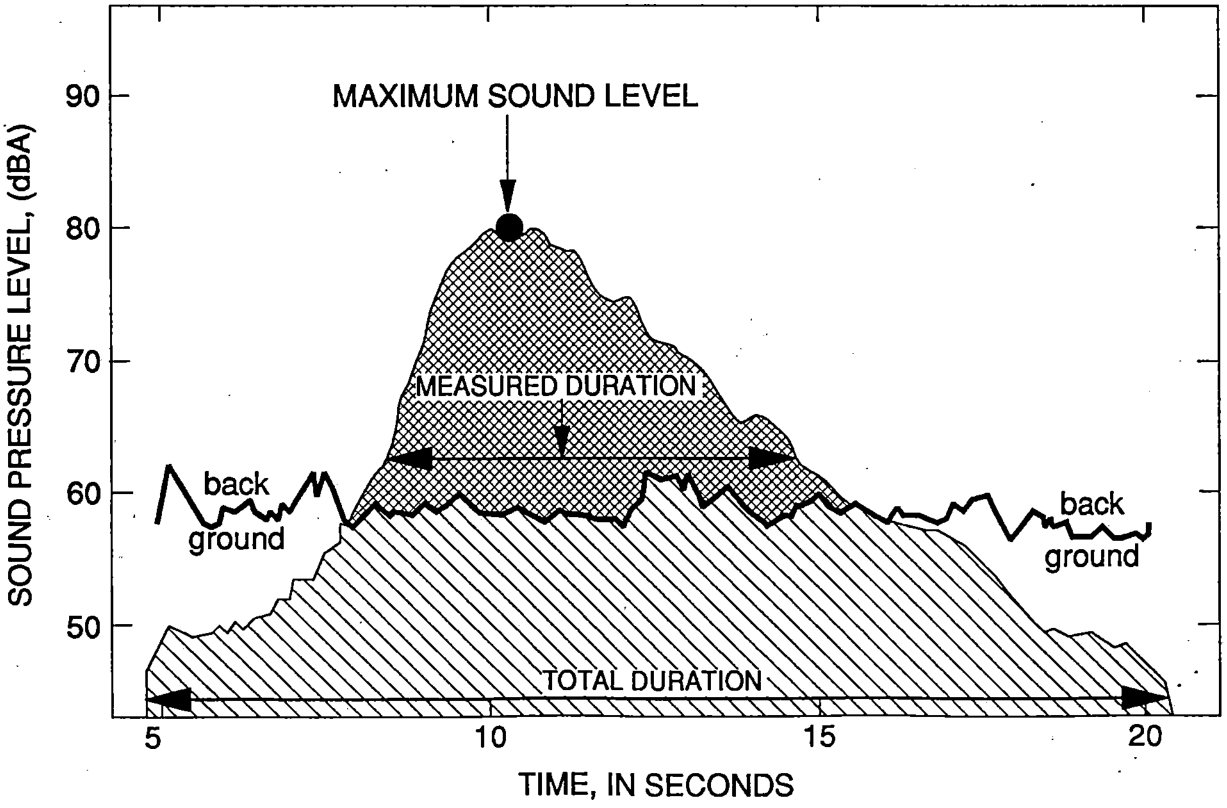

Figure 1. Typical Noise Time History of a Vehicle Passby

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).

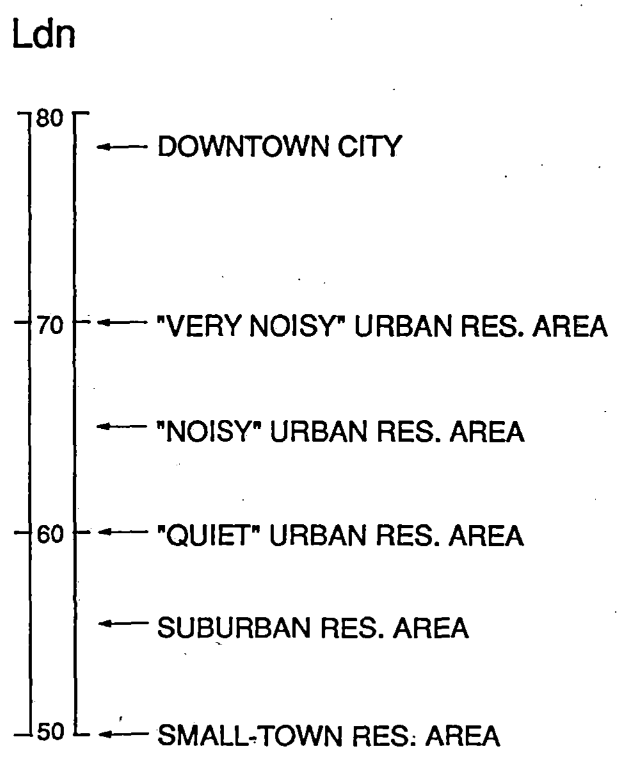

Figure 2. Typical Community Noise Levels, L_{dn}

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.

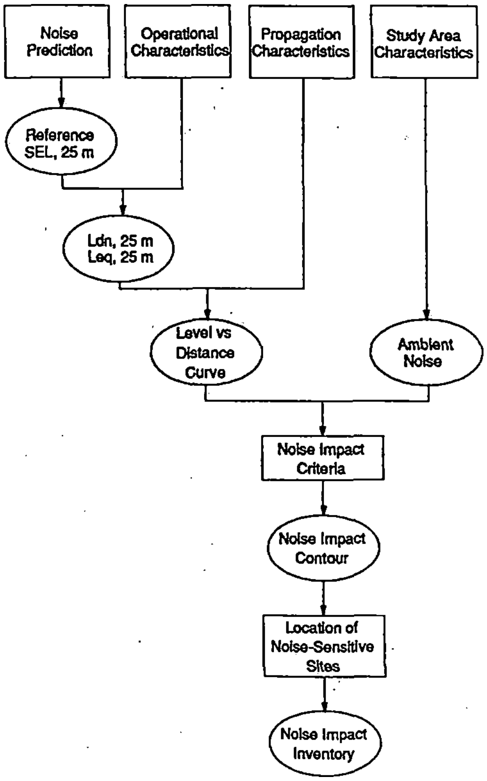

Figure 3. Procedure for Maglev Noise Assessment

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.

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

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

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

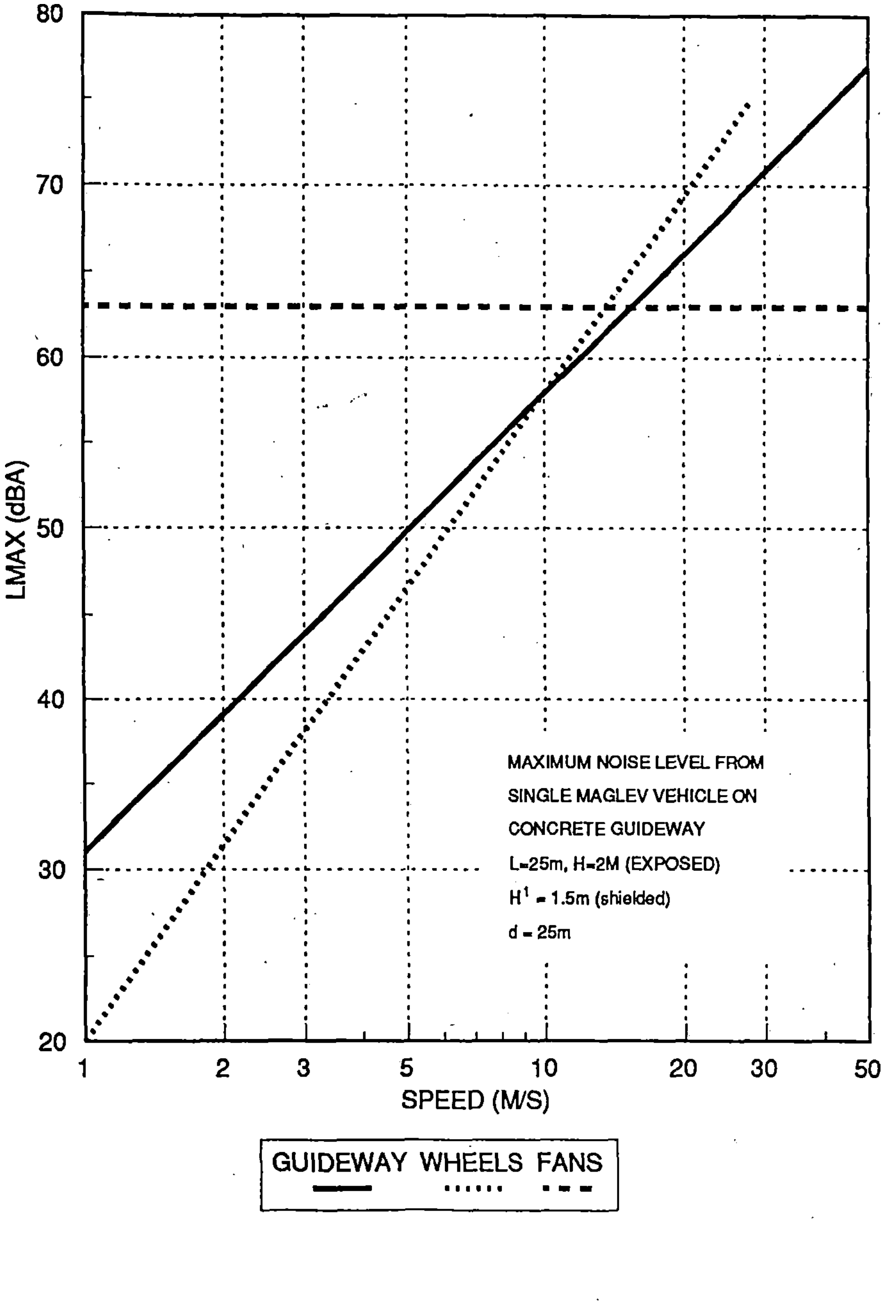

Figure 4. Maglev Noise in Low Speed Range, 0 to 42 m/s

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:

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

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

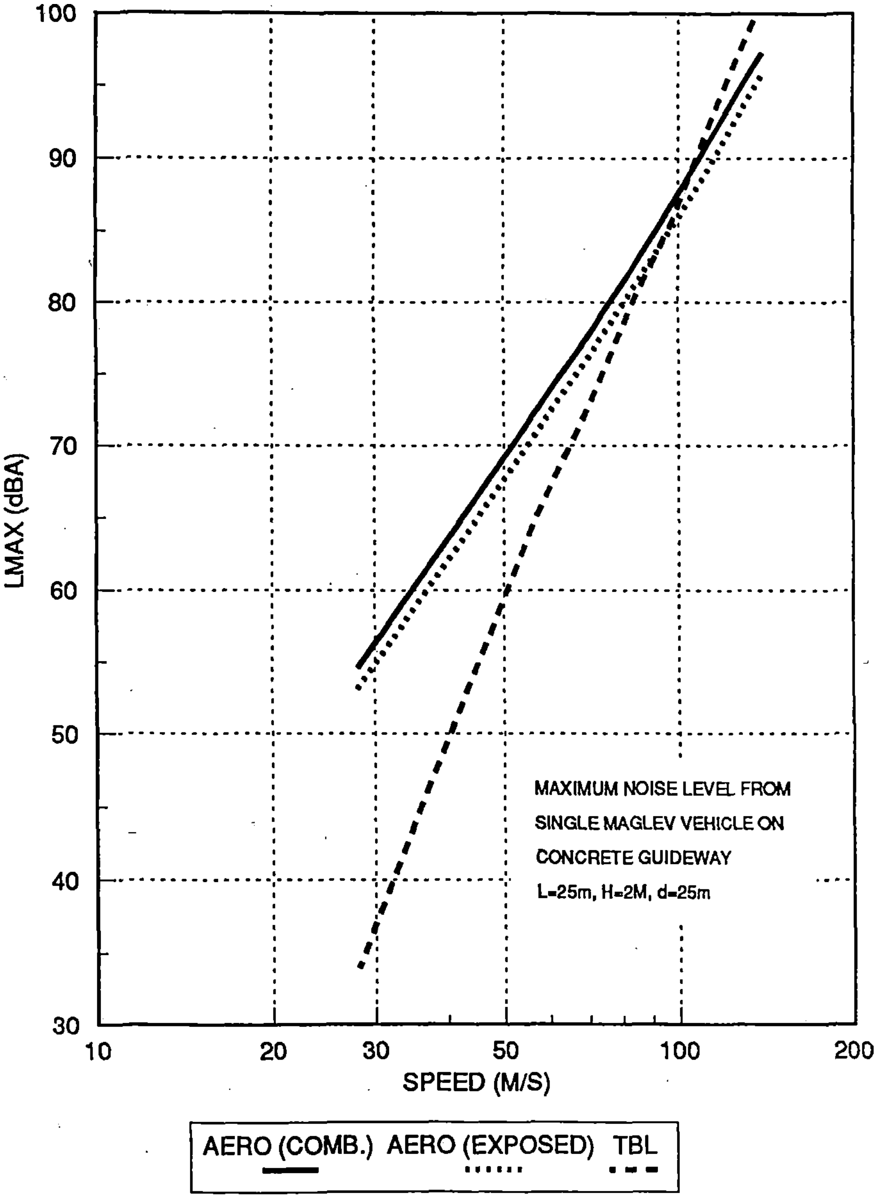

Figure 5. Maglev Noise at High Speed, greater than 42 m/s

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 the 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)**.

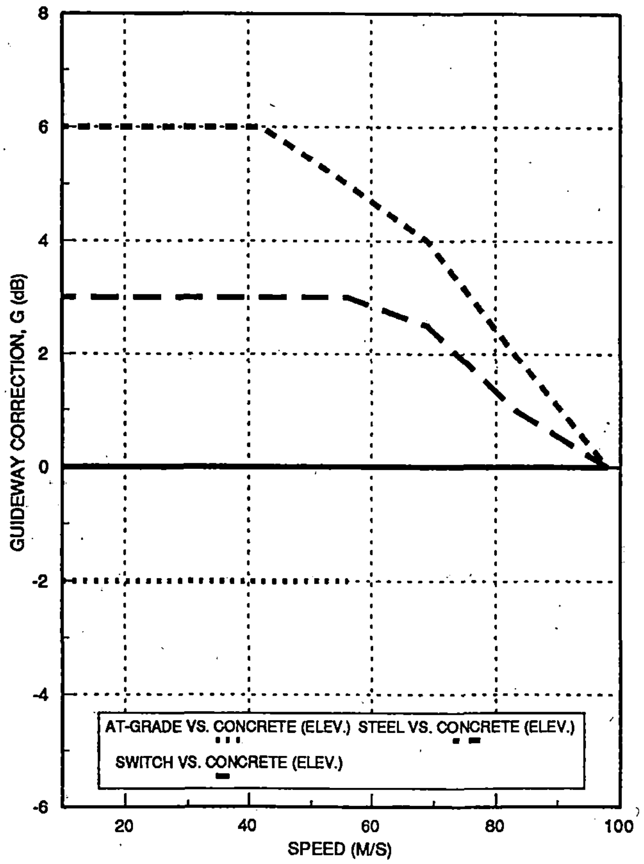

Figure 6. Guideway Noise

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:

$$\begin{aligned} Leq_{hour} &= \text{Energy Sum of all SEL's in one hour} - 10 \log_{10} 3{,}600 \\ &= \text{Energy Sum of all SEL's in one hour} - 35.6\text{dBA}, \end{aligned}$$

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.

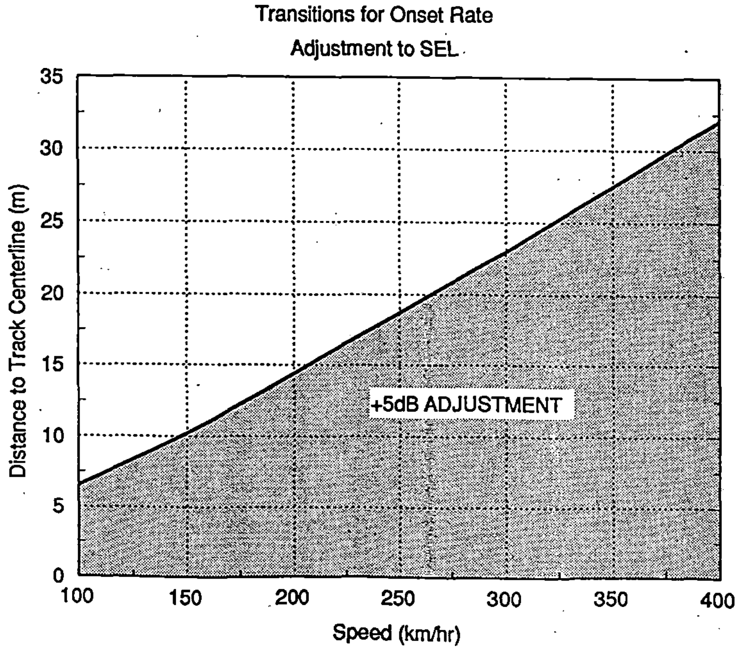

Figure 7. Adjustment for Startle from Maglev Noise

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.

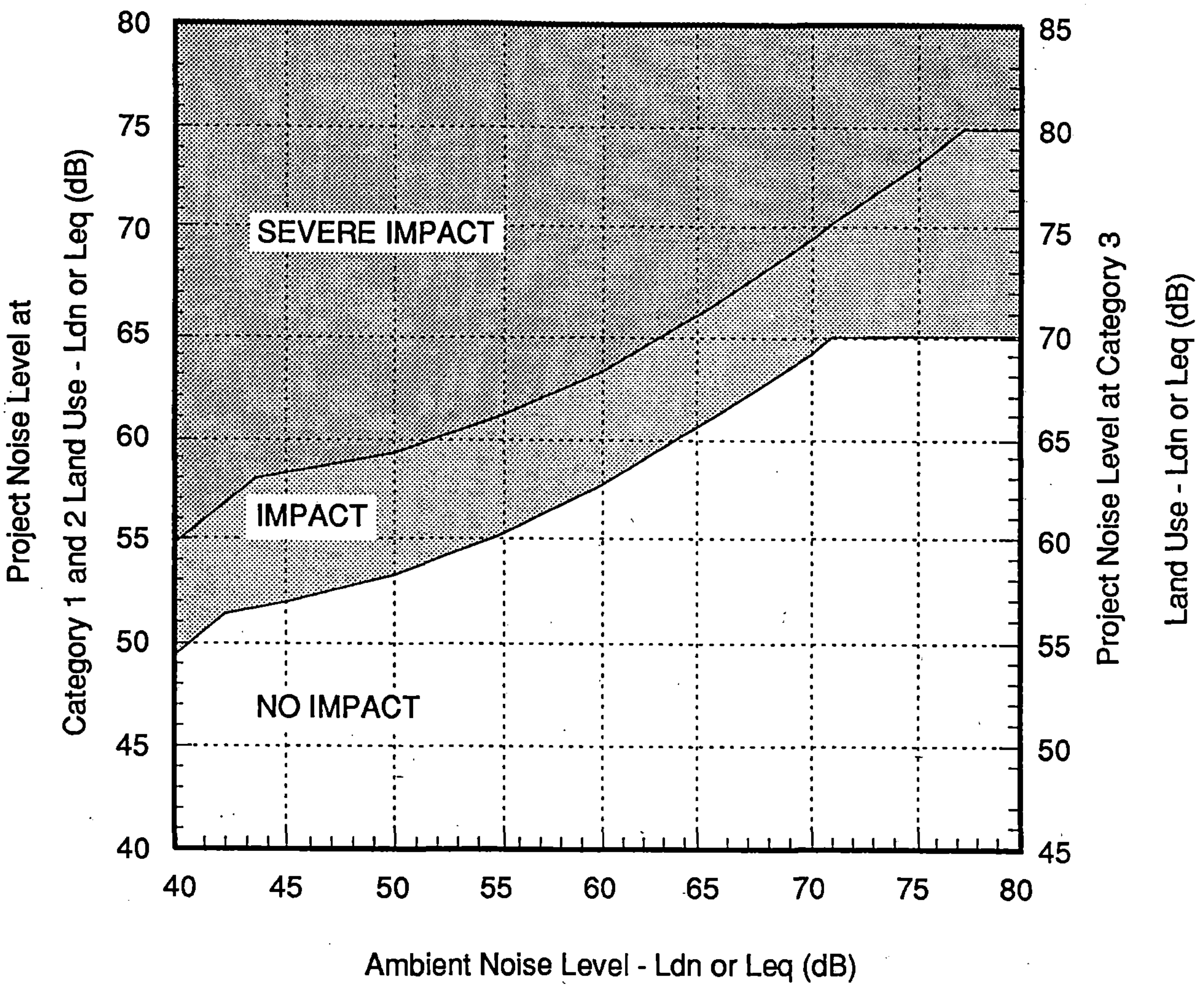

Figure 8. Noise Criteria for Maglev

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.

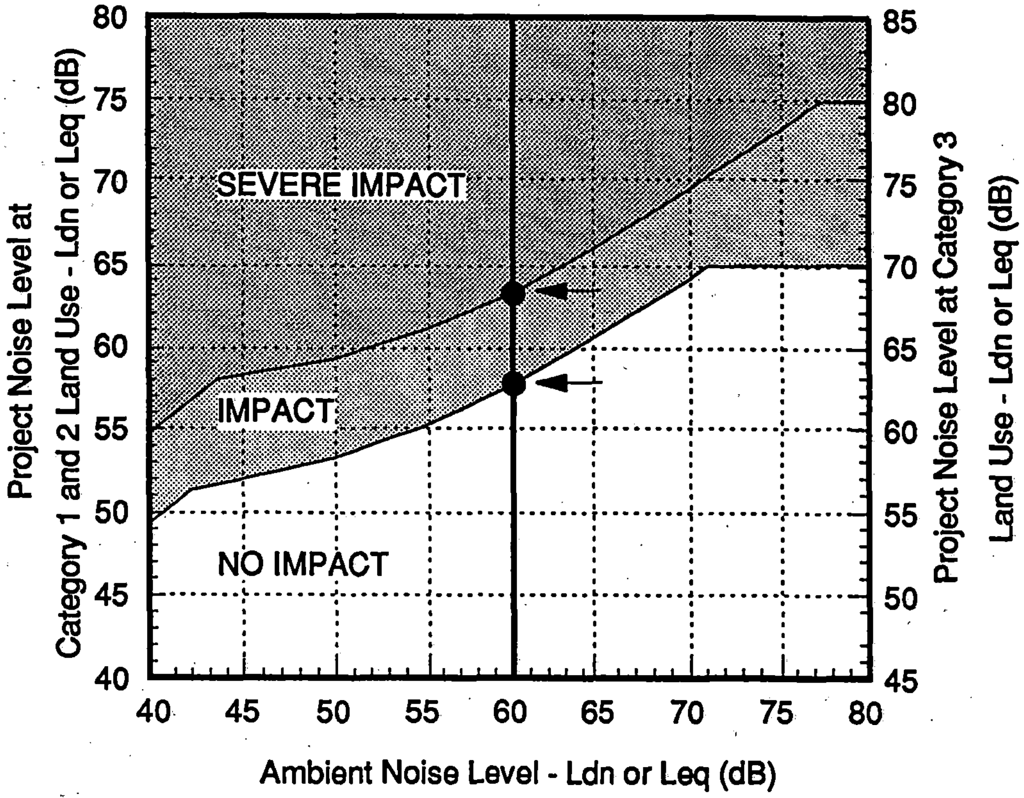

Figure 9. Example of Noise Impact Assessment

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.

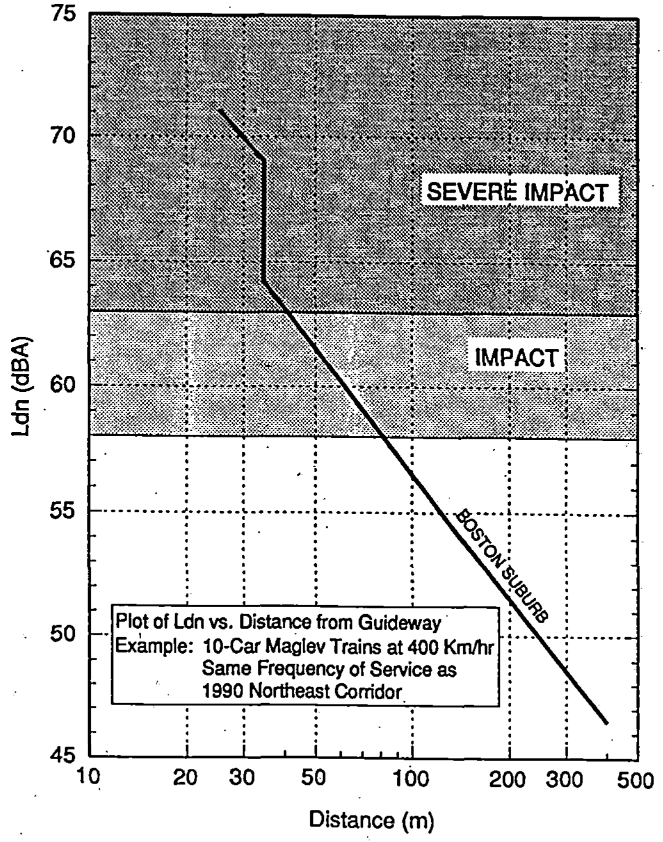

Figure 10. Ldn vs. Distance for Example

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.

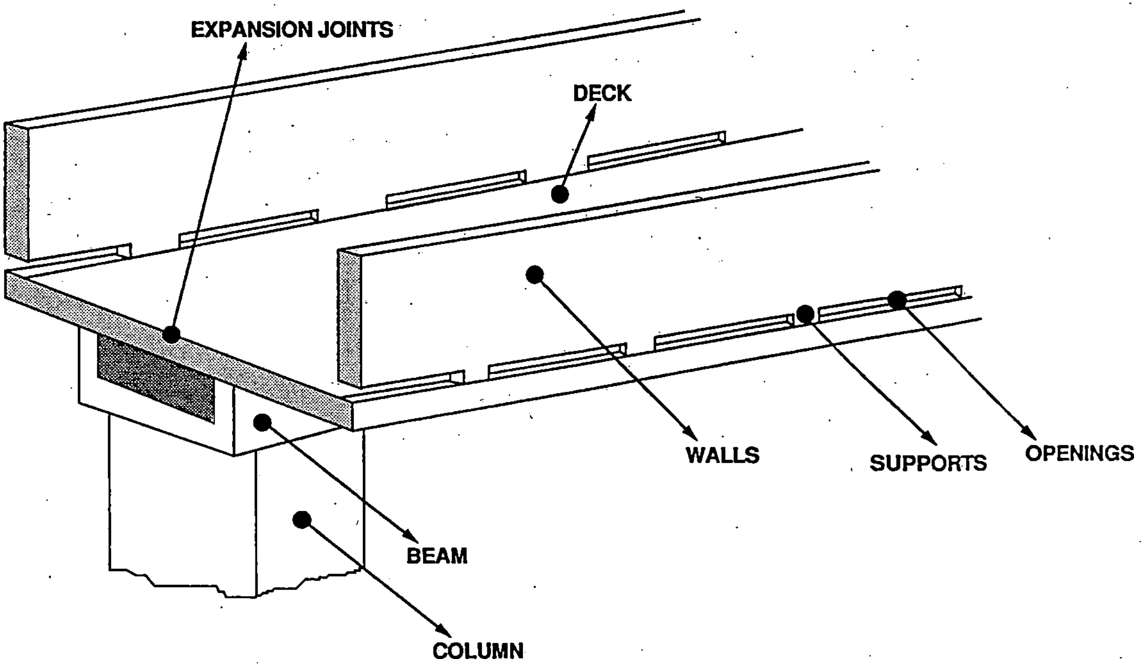

Figure 11. Guideway Structural/Mechanical Noise Sources

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.

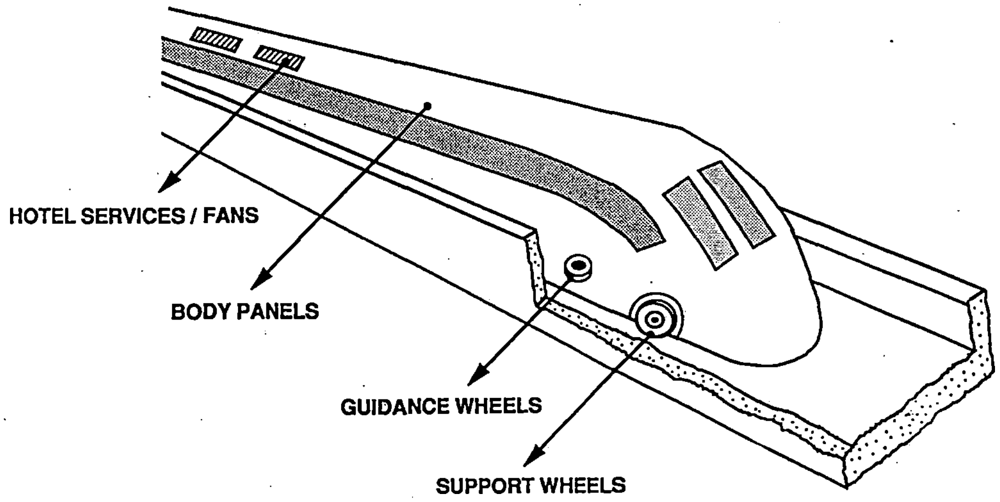

Figure 12. Vehicle Structural/Mechanical Noise Sources

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:

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

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.

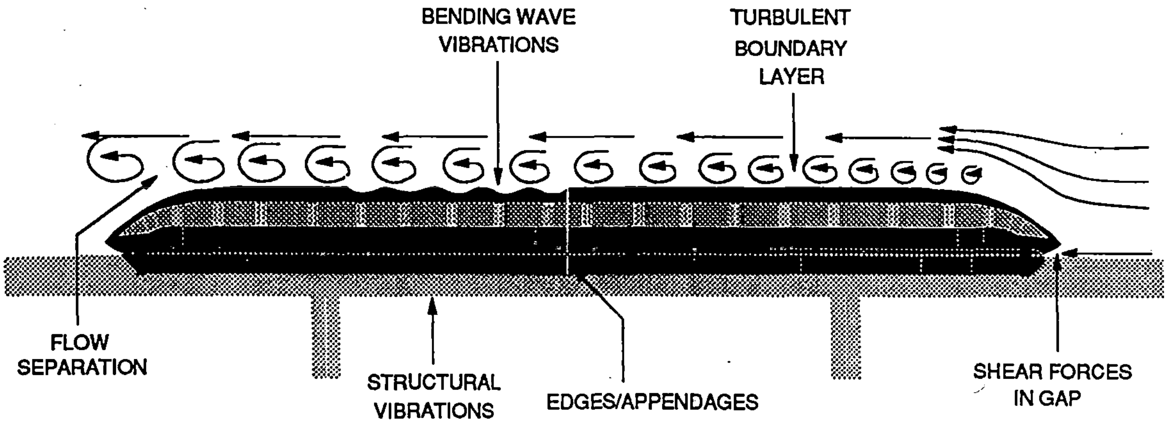

Figure 13. Vehicle Aeroacoustic Noise Sources

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 TBL. The 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

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[*] 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

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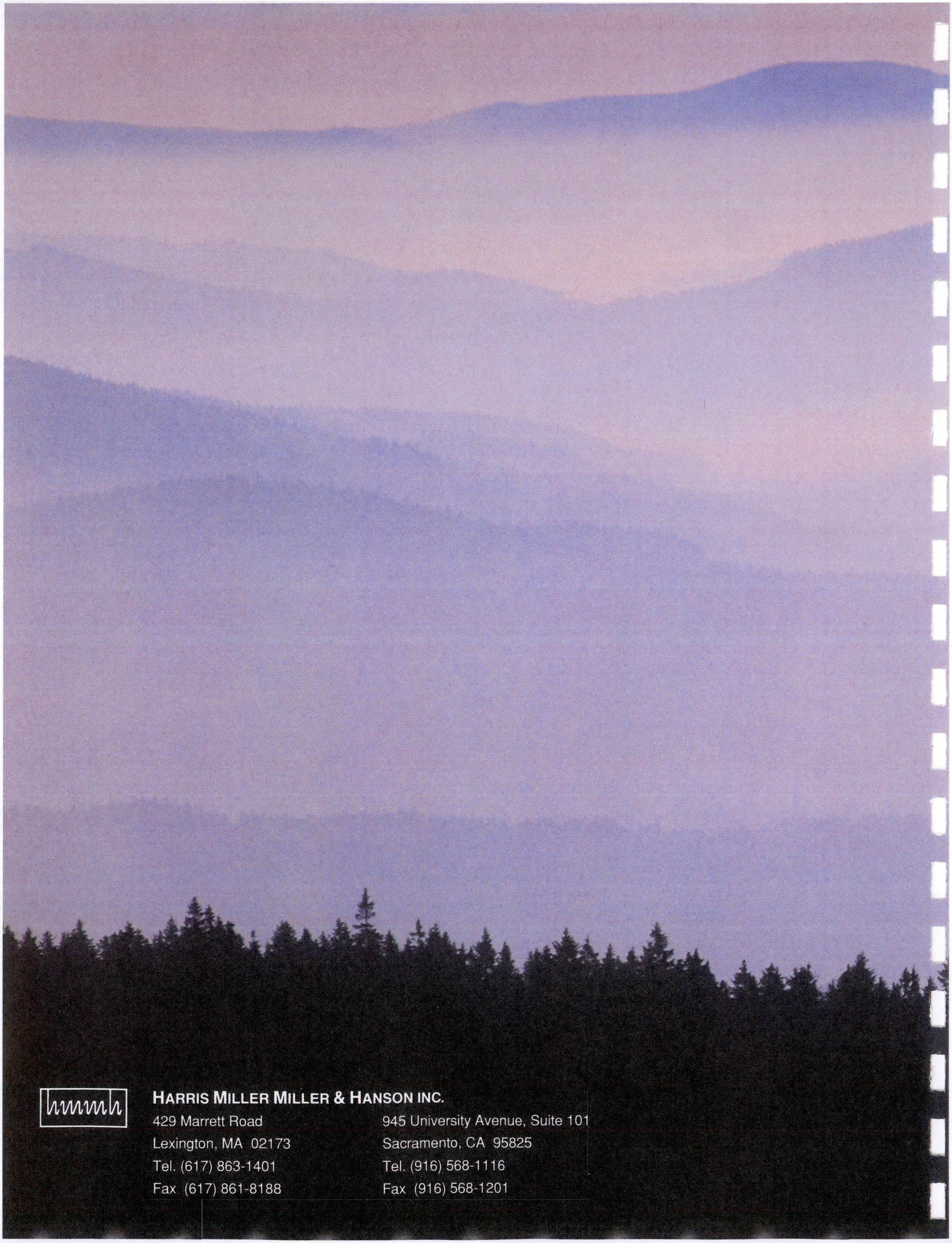

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