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Insertion Loss: Train & Light-vehicle Horns and Railroad-crossing Sound Levels

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Studies and analyses of sound levels inside road vehicles frequently require estimation of the sound levels of moving or changing positions of the source (such as a train horn) and receiver (road vehicle or other structure). The study presented here focuses on two of the components of the sound transmission from the source to the interior of an automobile. One part of the paper analyzes the attenuation of the sound level due to transmission through vehicle bodies and is related to annoyance of vehicle exterior noise. Insertion loss values and insertion loss spectra are measured for six different light vehicles. An unusual property of insertion loss spectra is observed and studied. It is shown that direct subtraction of measured band-filtered levels can provide misleading overall levels. A method of correction of the spectrum is presented.

The second portion of the sound path covered in this paper is the development of a method to predict the attenuation of the sound level over the path from the source to the vehicle. The method is based on the classical sound decay equation (including variable directivity and theoretical 6 dB drop-off per doubling of distance) but is modified to accommodate different drop-off rates including experimentally measured values. An example using a typical train horn sound power level is provided.

INTRODUCTION

The precursor to the horns on modern locomotives are the whistles from the venerable steam locomotives. Modern-day horns, which are pneumatically driven rather than steam driven, have been crafted to sound similar to the steam whistles. Modern train whistles are almost exclusively manufactured with three or five "chimes." Each chime, also referred to as a flute, is a separate noise source (horn) with the fundamental frequency differing between the chimes making them a horn system. The acoustic performance of train horns is regulated by the federal government[1].

The horns are used as, among other purposes, a warning device at grade crossings. Due to the importance of this safety function of train horns, numerous studies have been conducted examining their performance and operating characteristics. The acoustical characteristics and performance of three and five chime horn systems has been studied including the directivity of the acoustical output[2,3], the effect of installation location on the sound level output[3,4], the frequency spectra of horns[2,4] and the effect of the speed of the locomotive on the sound levels[5].

Studies have been conducted, primarily in the last twenty years, attempting to understand the effectiveness of the horns in alerting drivers to the presence of an approaching train. Some of the studies focus on the circumstances surrounding specific accidents[6] whereas other studies take a more general approach to the problem. The general approach typically involves looking at the various portions of the acoustical transmission path from the horn (the source) to the driver of the vehicle (the receiver) or to other receivers such as inside nearby structures. The three main portions of the path are the transmission through the air and over terrain to the vehicle (and its associated losses), the transmission across the vehicle body (and its associated losses) and the detectability and audibility of the sound to the receiver.

Numerous studies have looked at the detectability and audibility process[5,7,8,9,10]. These studies typically evaluate the ability of human subjects to detect and identify various acoustical signals (usually recordings of locomotive horns) while driving or performing a suitable task under various conditions. Because of the many variables involved a consensus has not been reached regarding a detectability or auditory threshold which can be generally applied.

The study to follow investigates two of the portions of sound transmission from the source to the interior of a vehicle. The first is the measurement of the attenuation of the sound level due to transmission through automobile bodies. This attenuation is frequently characterized by the quantity known in the field of acoustics as the insertion loss (IL). Insertion loss is defined[11] as the difference, in decibels, between two (overall) sound pressure levels (or power levels or intensity levels) which are measured at the same location in space before and after an acoustical device is inserted between the measurement location and the sound source. The ramifications of applying this definition to frequency band data is investigated. The use of insertion loss to quantify the attenuation in sound level related to automobiles has been studied[12,13,14] and has found application to train horns and automobiles at railroad grade crossings.

The second portion of the sound path investigated here is the development of a method to predict the attenuation of the sound level over a path from a train horn to a receiver. This method is based on classical acoustical theory. A model that characterizes this reduction in level[11], which ideally predicts a 6 dB reduction for a doubling of distance, is modified to take into account experimentally measured attenuation, or drop-off rates.

This paper includes an example that presents an application of the method to predict a range of the likely sound level inside a vehicle located at several positions from a train horn based on sound level measurements of the train horn. The main focus of this paper is the insertion loss of typical light road vehicles and the prediction of sound levels at railroad grade crossings. Related topics such as psychoacoustics of drivers, awareness, audibility, detectability and signal-to-noise ratios are not discussed.

SOUND LEVEL MEASUREMENTS

Measurement Location & Site Ambient Levels

Measurements of sound levels outside and inside seven light road vehicles were made outdoors over a flat asphalt surface surrounded by an open grassy area. The nearest vertical reflecting surface, an angled 2-story rectangular commercial building with a textured concrete surface, was approximately 500 ft (152 m) away. Weather was clear and sunny with temperatures between 80 to 86 °F (27 to 30 °C), average wind speed of 4.6 mph (7.4 km/h) and relative humidity of approximately 34%.

Three measurements were made of the outdoor site ambient sound levels, at the beginning, during and at the end of measurements. Figure 1 is a plot of the ⅓-octave ambient spectra of the three measurements. The average (10 Hz to 20,000 Hz) overall sound pressure level of all three measurements is 52.6 dBA.

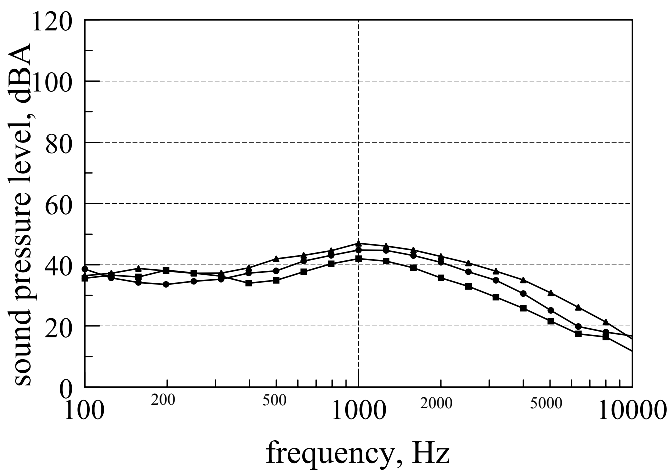

Figure 1. Ambient sound levels at the measurement site.

Vehicles and Measurement Geometry

The participating vehicles are listed in Table 1 along with their Vehicle Identification Numbers (VIN). The Lincoln MKZ horn was used as the sound source for measurements of exterior and interior levels in all other vehicles. Horn levels of the Lincoln MKZ and the Honda Odyssey were measured for comparison.

All measurements were made over a flat asphalt roadway surface. The vehicle and sound level meter (SLM) experimental layout is illustrated in Fig 2 where *m* indicates the microphone position for the horn sound level measurements (with no receiver vehicle present), r_m indicates distance of the SLM microphone from the top of the bumper of the source vehicle, S, and r_d indicates the distance to the microphone for measurements at the driver's head position in the receiver vehicle, R. The position *m* was 4 ft (1.2 m) above the ground and 11.5 ft (4.1 m) horizontally from the front bumper of vehicle S. The top of the front bumper for the MKZ is nominally 1.8 ft (0.53 m) above

Table 1, Participating Vehicles

Vehicle	VIN
2003 Honda Odyssey	5FNRL180X3B08XXXX
2003 Ford Windstar	2FMZA514X3BB7XXXX
2002 Honda Civic	1HGES16512L00XXXX
1998 Chrysler T & C	1C4GP64L3WB64XXXX
1998 Ford Windstar	2FMZA5146WBC4XXXX
2007 Ford Focus	1FAHP37N87W29XXXX
2001 Honda CRV	JHLRD18451C00XXXX
2007 Lincoln MKZ (source)	3LNHM26T87R60XXXX

the ground. This makes r_m = 11.7 ft (3.6 m). The corresponding distance for the interior microphone position measurements is r_d = 14.7 ft (4.5 m). Measurements were not made at the recommended distance[15] from the source of 23 ft (7 m). The distance of 11.7 ft (3.6 m) was chosen as a trade off in order to obtain reasonably high sound levels over the exterior of the vehicles whose interior sound levels were being measured and to make the sound measurement position lie beyond the near field of the source for frequencies above 100 Hz (a distance equal to or greater than one wavelength away from the source).

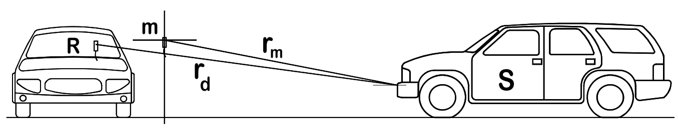

Figure 2. Measurement geometry

Instrument

Measurements were made using a calibrated CESVA Model SC 310, Type I (IEC, ANSI) integrating sound level meter. The Model SC 310 is equipped with a ½ in. (13 mm) capacitor microphone. All measurements were carried out using the ⅓-octave band feature from 10 Hz to 20,000 Hz. A wind screen was used with all measurements. In all cases, sound levels were collected and analyzed digitally over 10, 1-sec intervals.

Vehicle Horn (Source) Levels

The intention here is to determine the acoustic insertion loss of light road vehicles with a train horn as the source. Train horns are difficult to obtain and operate for purposes of testing. It has been suggested[16] that light vehicle (cars, vans, SUVs, pickup trucks, etc.) horns can be used successfully to determine insertion loss. This was done here.

Light Vehicles: To determine information about source power levels and directivity, sound levels were measured in the absence of any receiver vehicle for two source vehicles (Lincoln MKZ and Honda Odyssey) directly in front of each vehicle and at lateral angles of 45° and 90° to the driver's side. Figure 3 shows the levels measured. The sounds from the two cars exhibit different fundamental frequencies and have different sounds. Both show differences associated with directivity. The overall level (10 Hz to 20 kHz) at 0° of the Odyssey was 102.7 dBA and the MKZ, 100.1 dBA. Comparisons of Fig 3 with Fig 1 shows that the horn levels at frequencies below about 250 Hz were near to or slightly above the ambient levels. This indicates that the horns likely emit little acoustical power below about 250 Hz.

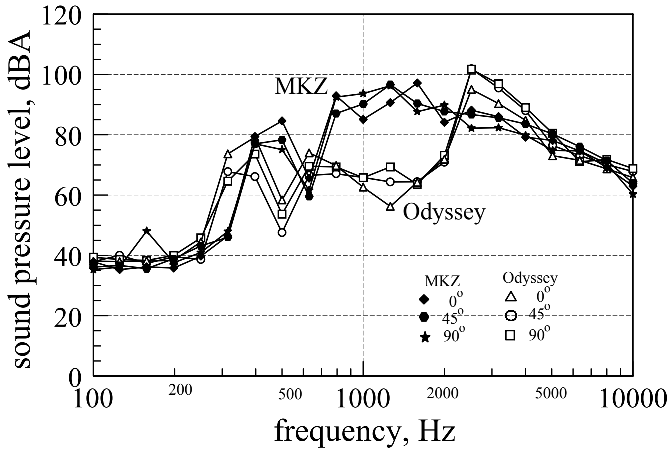

Figure 3. Spectra of two vehicle horns, Lincoln MKZ and Honda Odyssey.

Measurements of the source levels were made at position *m*, not at the driver's head position. To make comparisons and to compute insertion loss, the levels at the driver's head position were estimated using the measured levels at *m*, for the MKZ. This can be done using the equation[11]:

$$L_P = L_W + 10\log\frac{Q(\theta)}{4\pi r^2} \tag{1}$$

where L_P is the sound pressure level at the receiver, L_W is the sound power level of a (point) source, $Q(\theta)$ represents the source directivity and $r = r_d$ is the distance between the source and receiver. For $Q(\theta) = 1$, an effective sound power level of the MKZ horn for a point source at the top of the bumper (see Fig 2) can be determined using the measured value of L_P = 100.1 dBA and the distance r = 11.7 ft (3.6 m). This gives an overall sound power level of L_W = 122.0 dBA. With this value of sound power level, Eq 1 can then be used to determine that L_P = 98.1 dBA for r_d = 14.7 ft (4.5 m). This is approximately 2 dBA lower than the level measured at r_m. Consequently, L_P = 98.1 dBA was used to calculate the insertion loss at the driver's head position from measurements made inside each vehicle.

Train Horns: Measurements have been made of the spectral characteristics of train horns[2]. The ⅓-octave band sound levels were measured and are reproduced in Fig 4. In some ways, the acoustical characteristics are similar to car horns in that they have their highest output between 250 Hz to 10 kHz, which encompasses the frequency range of highest sensitivity of human hearing (1 kHz to 5 kHz[17,18]).

Levels Inside Light Vehicles

Insertion Loss: Each of the first six vehicles listed in Table 1 was parked at position R with the orientation indicated in Fig 2. The horn of the MKZ was sounded for a duration of 10 sec and the level was measured with the microphone inside the vehicle at the driver's head position. This was done with the receiver engine running, no vehicle accessories operating and for three conditions: *0*, all windows fully closed in vehicle R, *1*, the driver's window open approximately 1 in. and *2*, the driver's window fully opened (all other windows fully closed). Table 2 lists the overall interior levels for the different window-open positions and the overall insertion loss values. Insertion loss was computed by subtracting the measured overall sound levels in the vehicle (10 Hz to 20kHz) from the overall MKZ horn sound pressure level at the driver's head position (98.1 dBA). Rapoza, et al.[13] report that open windows cause a decrease in insertion loss of approximately 5 to 15 dB (from the closed-window condition). Results here indicate a larger difference, from 15 to 23 dBA, for ~1-inch opening and 27 to 36 dBA for fully opened.

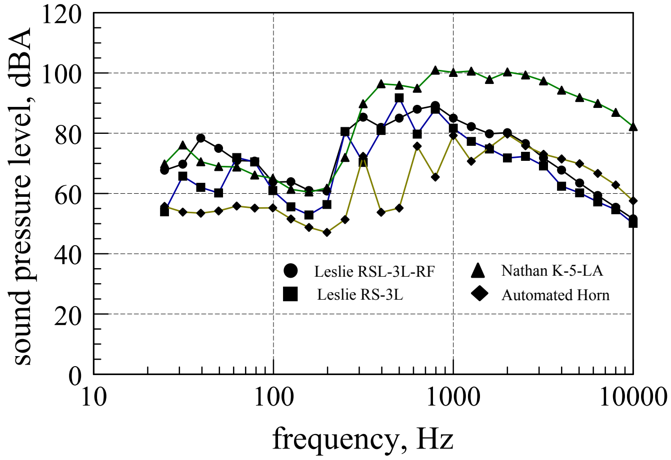

Figure 4. Train horn spectra[2]

Table 2, Insertion Loss, dBA

Vehicle	Interior level, dBA			Insertion loss, dBA		
	0	*1*	*2*	*0*	*1*	*2*
'02 Honda Civic	64.2	84.8	94.3	33.9	13.3	3.8
'01 Honda CRV	67.2	82.6	94.4	30.9	15.5	3.7
'03 Honda Odyssey	63.2	85.9	94.2	34.9	12.2	3.9
'03 Ford Windstar	61.2	83.5	96.7	36.9	14.6	1.4
'98 Ford Windstar	61.4	81.6	93.7	36.7	16.5	4.4
'07 Ford Focus	64.2	83.9	91.4	33.9	14.2	6.7
'98 Chrysler T & C	67.1	85.1	93.6	31.0	13.0	4.5
Average Insertion Loss, dBA				35	14	4
Standard Deviation, dBA				2.4	1.5	1.6
Range, dBA				31 - 37	12 - 17	1 - 7

Measurements of insertion loss of road vehicles have been made by others. Dolan and Rainey[9] made dynamic measurements of the insertion loss over a 35-sec duration of moving train horn sounds for three vehicles with closed windows, a 1989 Toyota pickup truck, a 1999 Toyota 4-Runner SUV and a 2001 Pontiac Grand Prix sedan. The overall vehicle insertion loss values were 25.4, 27.1 and 28.0 for the pickup, SUV and sedan, respectively. Rapoza, et al.[13] measured insertion loss for three different sound incidence angles relative to vehicle heading and found that it did not vary significantly between the angles.

Vehicle	Insertion Loss
1986 Freightliner cab-over truck tractor	17
1996 Freightliner conventional truck tractor	18
1996 Thomas/International school bus	21
American La France fire truck	21
1990 Ford F-350 ambulance	27
1997 Thomas/Ford school bus	27
1978 TMC Crusader coach bus	28
1994 Dodge Ram 1500 pickup truck	26
1996 Ford F-250 pickup truck	28
1987 Mercedes 300 SDL turbo	29
1995 Oldsmobile Achieva	32
1986 Chevrolet Corvette	33

Table 3, Insertion Loss, dBA[19]

An NTSB study[19] reports on measurements of the insertion loss of a variety of vehicle types. The sound source was a train horn at a distance of 96 ft from the vehicle. The insertion loss levels are given in Table 3. Measurements comparable to those reported here are those of the light vehicles, the last five vehicles listed in Table 3 which arithmetically average to 30 dBA.

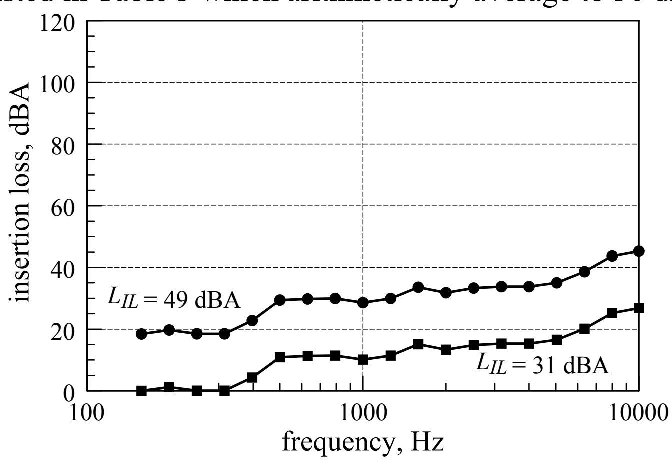

Figure 5. Insertion Loss: ● Rapoza, et al.[13], ▪ modified (see next section).

Rapoza, et al.[13] measured the insertion loss of seven light vehicles using loudspeakers and pink noise as a source. Overall levels were described as ranging between 25 to 35 dBA. Individually measured overall values from each vehicle were not reported. The values actually published in the report were in the form of spectra, calculated by subtracting each ⅓-octave band level measured inside the vehicle from each corresponding ⅓-octave band level measured without a vehicle. Results of those measurements averaged for all vehicles are shown in Fig 5. Unfortunately, the published ⅓-octave spectral results cannot be used to calculate the overall insertion loss level. This is clear by recognizing that the calculated overall level of the data (●) in Fig 5 is 49 dBA, well above the reported range of 25 to 35 dBA. Spectral values calculated in the same way from the light-vehicle horn level data collected in the work reported in this paper, Fig 3, also were unreasonably high. They ranged from 52 to 60 dBA whereas the measured overall levels are seen from Table 1 to range from 31 to 37 dBA. The reason for this disparity and a correction method are discussed in the next section and in the Appendix.

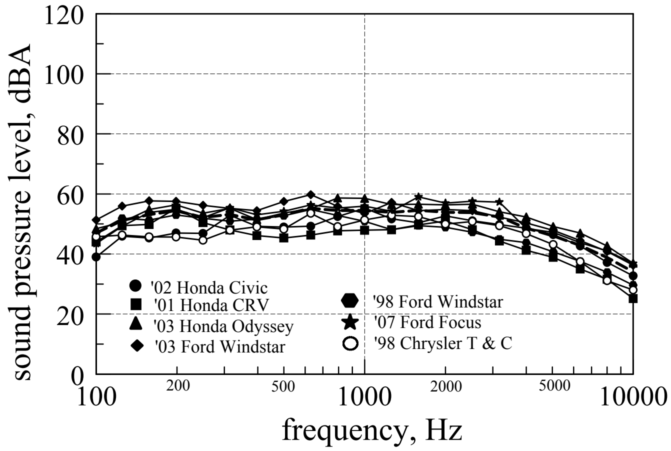

Figure 6.Vehicle interior sound spectra with engines running, air conditioners operating and fan on high.

Ambient Level from Air Conditioning Fans: In addition to the sound levels due to the exterior horn source, levels were measured inside each of the vehicles listed in Table 1 at the driver's head position with all windows closed, the engine idling, air conditioning turned on and with the fan set at its highest position. Figure 6 shows the ⅓-octave band levels for all cars. Overall levels ranged from 62 to 68 dBA. Spectra such as these which are relatively flat over the audible frequency range, in this case 100 Hz to 10000 Hz, are referred to as broadband sounds. In this case the levels begin to drop somewhat above about 3000 Hz.

CORRECTED INSERTION LOSS SPECTRA

As noted earlier, subtraction of individual ⅓-octave band spectral frequency decibel levels does not produce a meaningful insertion loss spectrum. An approach is presented here that develops an equivalent, or corrected, mean-square-pressure insertion loss. The method establishes a spectrum in the traditional sense that, when summed, produces the same overall level of insertion loss as obtained by subtraction of the overall levels, the definition of insertion loss. Suppose L_{Pf} is the sound pressure level of a source measured at a given position and filtered with a band centered at frequency *f*. Suppose L'_{Pf} is the sound pressure level at the same point filtered with ⅓-octave band center frequency *f* but following insertion of a sound barrier. The difference in these levels is

$$\Delta_f = L_{Pf} - L'_{Pf} \qquad (2)$$

The corresponding mean-square-pressure of this difference for each frequency band is

$$\left(\frac{p^2}{p^2_{ref}}\right)_f = 10^{(\Delta_f/10)} \qquad (3)$$

where p^2 is the mean-square acoustic pressure and p^2_{ref} = 20 μPa. An *equivalent* mean-square-pressure insertion loss is defined for a frequency band centered at frequency *f* as

$$a\left(\frac{p^2}{p^2_{ref}}\right)_f = a10^{(\Delta_f/10)} \qquad (4)$$

where a is a constant, independent of f. The constant a is determined by summing each filtered mean-square pressure values over all spectral frequency bands to determine the overall level and equating it to the measured overall insertion loss. That is,

$$10log\sum_f a\left(\frac{p^2}{p_{ref}^2}\right)_f = IL_{OVL}^{meas} \tag{5}$$

For example, the overall measured insertion loss for the 2002 Honda Civic (Table 2, Case *0*) is

$$IL_{OVL}^{meas} = 33.9\ dBA \tag{6}$$

Subtraction and correction of the spectral values requires that the constant a have the value $a = 1.25\times10^{-2}$ for the Honda Civic. The spectra for the 2002 Honda Civic and all other vehicles listed in Table 2 are shown in Fig 7, in both corrected and uncorrected forms. Based on the seven vehicles measured, Fig 7 shows that the corrected insertion loss of typical road vehicles is significant for frequencies only above 315 Hz and both corrected and uncorrected insertion loss spectra remain relatively constant above 1580 Hz.

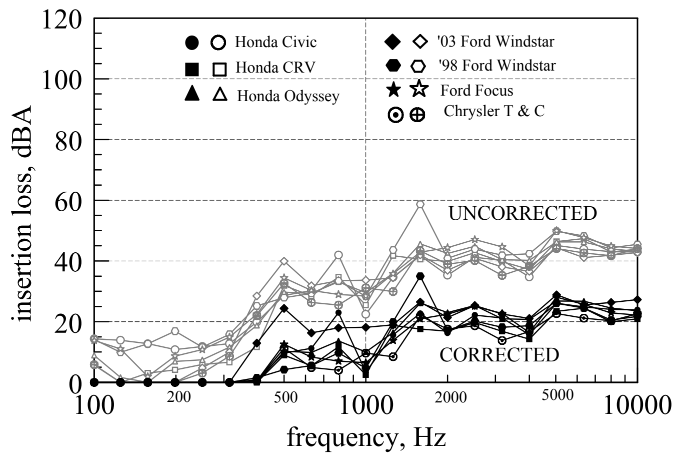

Figure 7. Insertion loss spectra, uncorrected and corrected.

Corrections of insertion loss spectra are useful not only for complete spectra but may be necessary when processing levels over portions of the audible frequency range. As an example, first consider that the standard A-weighting correction curve has maximum values between 762 Hz and 7773 Hz. This can be said to be a range of maximum human hearing sensitivity because values of the A-weighting correction exceed -1.0 dBA between these frequencies (see Fig 8). If insertion loss over a limited range such as this is needed, it is necessary to use the corrected spectrum. Using the measurements of Rapoza, et al.[13] in Fig 5 the insertion loss in the range $762 \leq f \leq 7773$ Hz is 25 dBA whereas the overall value is 31 dBA. A further presentation of the mathematics of this problem is contained in an appendix to this paper.

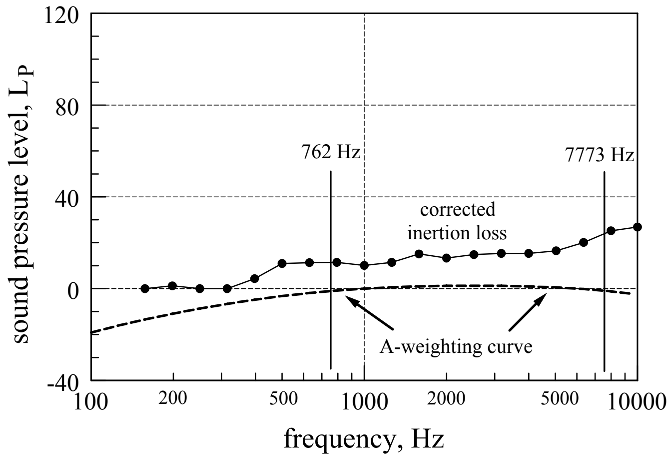

Figure 8. Sub-spectral insertion loss, measurements of Rapoza, et al.[13].

COMPUTATION OF HORN SOUND LEVELS AT A DISTANCE FROM A POINT SOURCE

Under idealized conditions, the use of Eq 1 allows the estimation of the sound pressure level, L_P, at a receiver position, *R*, at a distance *r* from a point source, *S*, with known sound power level, L_W. This approach, along with experimental measurements, can be made more useful for prediction of the sound level at various relative positions of a source and receiver. Consider the railroad crossing illustrated in Fig 9 with a locomotive horn as a source, S, and a road vehicle as a receiver, R. The angles α and γ define the roadway and track geometry and d_L and d_V are the respective distances of the locomotive front and vehicle driver from the center of the crossing center, *C*. The distance h_S is the horn setback, the distance from the front of the locomotive to the horn position. The directivity $Q(\theta)$, in Eq 1, reflects the change in the sound power of the source as it varies with

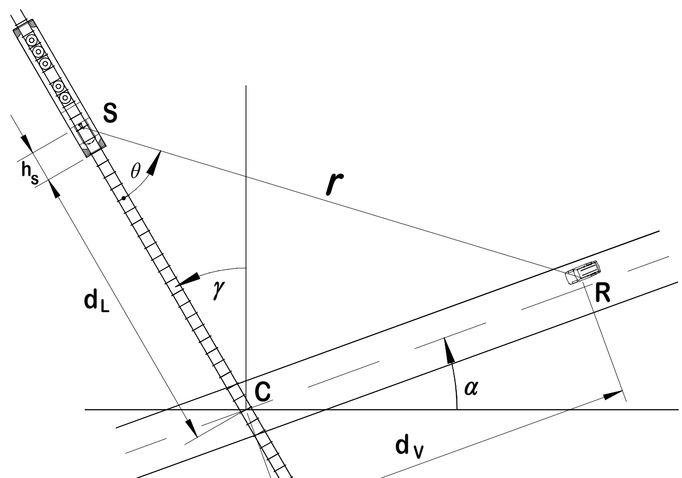

Figure 9. Railroad highway crossing geometry.

the angle θ. This permits changes in sound radiation of the source as the receiver is located at different angles relative to the heading of the source (locomotive), i.e. as θ changes.

For an omnidirectional source[11], $Q(\theta) = 1.0$, and Eq 1 predicts a drop-off based on spherical propagation of 6 dB per doubling of distance for all angles, θ. Measurements have indicated that, in practice, the level of the sound pressure can drop-off at rates different from 6 dB depending on the environment between the source and receiver. Using repeated measurements, Seshagiri and Stewart[6] found values over flat, snow covered ground to vary from 4.3 dB to 8.9 dB. In their work, Rapoza and Fleming[20] found that the drop-off rate for train horns varied from 5.7 to 8.4 dB, was inversely proportional to the height of the source above the ground and was approximately 6 dB for a horn height of 16 ft (4.9 m). In order to model different empirical drop-off rates, Eq 1 can be modified such that,

$$L_P = L_W + 10\log\left(\frac{Q(\theta)}{4\pi r^{2k}}\right) \tag{7}$$

where the constant k is introduced to allow varying drop-off rates. For distances r and $2r$, Eq 7 can be used to solve for k, giving

$$k = \frac{L_{P2r}}{20\log 2} \tag{8}$$

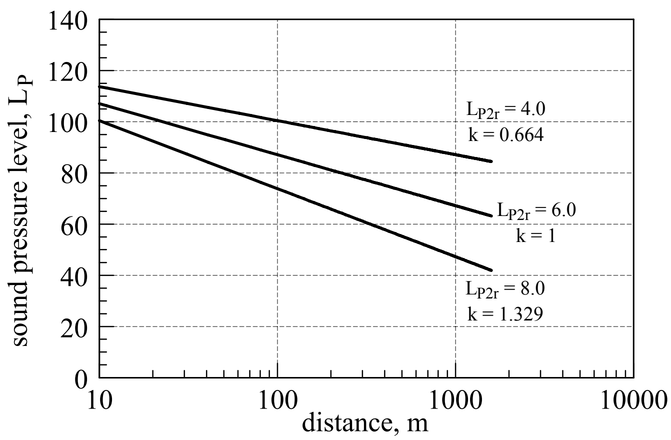

Figure 10. Sound pressure level as a function of distance, *r*, for different drop-off rates, *k*.

where $L_{P2r} = L_P(2r) - L_P(r)$ is the drop-off rate per doubling of distance in decibels. For example, a drop-off rate of 5 dB per doubling of distance needs a value of $k = 0.830$. For a drop-off rate of 8 dB per doubling of distance, $k = 1.329$. Drop-off rates computed using Eq 7 are independent of the source power level, L_W, and directivity $Q(\theta)$. Figure 9 shows differences in sound propagation for three different values of k.

Equations 7 and 8 can be used for computing individual frequency band values when the drop-off rate is a function of frequency. This would be the case, for example, when atmospheric attenuation or diffraction differ significantly with frequency. Once the spectral values are computed, the overall level can be computed by summation.

Table 4, Example, sound levels at R, dBA			
time to crossing, s	distance to crossing, ft d_V	d_L	L_P at R
10.0	440	733	71
5.0	220	367	78
3.45	152	253	81

Example: As an example, suppose a locomotive horn satisfies current Federal Railway Administration regulations[1] and produces an overall sound level of 96 dBA at 100 ft directly in front of the locomotive. For the locomotive height of 15 ft (4.6 m), horn setback of 30 ft (9.1 m) and a measurement height of 4 ft (1.2 m), this corresponds to a sound power level of L_W = 139 dBA. Assume the train horn is omnidirectional, $Q(\theta) = 1$, and the drop-off factor calculated from measurements at the crossing site is $k = 1.18$. The crossing and vehicle conditions are as follows: perpendicular crossing ($\alpha = 0°$, $\gamma = 0°$), the speed of the train is 50 mph (80.5 kph), the speed of the vehicle is 30 mph (48.3 kph). Table 4 gives three times and positions of the vehicles as they approach the crossing along with the corresponding sound pressure levels using Eq 7. The third time and distance, d_V, listed in Table 4, $t = 3.45$ s, corresponds to the stopping time[21] for a vehicle on a pavement with a frictional drag coefficient of $f = 0.7$ and a driver with a perception-decision-reaction time of 1.5 s. Knowing the sound levels at R, the appropriate insertion loss can be used to determine the sound pressure level inside the vehicle due to the train horn. For example, if the driver's window is fully opened, an insertion loss of approximately 4 ± 2 dBA can be subtracted from the values of L_P at R given in Table 4.

DISCUSSION AND CONCLUSIONS

Acoustical insertion loss has been measured for six light vehicles. The source of sound for the insertion loss was another vehicle's horn. Based on comparisons of the values of insertion loss measurements of other researchers using pink noise, train horns and car horns (the results obtained here), overall values do not appear to differ significantly. However, in order to draw a reliable conclusion concerning significant differences, a more complete study with statistical testing of results is necessary using identical vehicles and different horn sources is necessary.

It was shown that subtraction of individual band-filtered measurements, with and without a vehicle, to obtain a spectrum of insertion loss can produce misleading results. Spectral values obtained in such a way do not sum to the overall value of the insertion loss. It was shown that such a spectrum can easily be corrected, however. Using the method presented, the corrected and original spectra have the same shape but sum to different overall values. Insertion loss of sub-spectra must be handled this way.

Finally, it has been shown that the classical acoustical propagation equation, Eq 1, can be modified to produce a formula that models practical drop-off rates conforming to experimentally measured data. The modified form is shown in Eq 7. This equation, in turn, can be used to predict realistic sound pressure levels at positions different than the location of the experimentally measured data.

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APPENDIX: Calculation of the Insertion Loss from Spectral Data

Insertion loss (IL) is one of three metrics of performance criteria in the field of noise control, the others being noise reduction (NR) and transmission loss (TL). Insertion loss is defined[22,23] as the change in the overall sound pressure level at a fixed location in space relative to a source due to some modification in the acoustical environment between the source and receiver. In general applications of insertion loss, such as in industrial settings, the change typically takes the form of an enclosure placed over a device that is a source of noise. It is also commonly used in the measure of performance of mufflers, or silencers. The situation considered here is a variation of this use in that the measuring apparatus (sound level meter) is placed inside an enclosure while the source, outside the enclosure, remains unchanged. One common application of this geometry is the measure of the reduction in the sound pressure level from outside a vehicle to the inside of a vehicle in the presence of a sound source such as a train horn. The definition of a measure of insertion loss is given by the arithmetic difference in two sound levels:

$$IL_{OVL}^{meas} = L_{P1} - L_{P2} \qquad \text{(A-1)}$$

where L_{P1} is the overall sound pressure level at the location under the initial acoustical configuration (without an enclosure) and L_{P2} is the overall sound pressure level at the same location after the change in the acoustical environment (with an enclosure). In general, $L_{P2} < L_{P1}$, and Insertion Loss is positive; the opposite definition is sometimes used.

While the spectra of the sound pressure levels for L_{P1} and L_{P2} can be measured, the definition of insertion loss given in Eq A-1 yields a single value which quantifies the reduction of the sound level as a result of the change in the environment. A generalized notion of the spectrum of insertion loss has been presented[23] but the details regarding the means to calculate the spectrum are not considered. Calculating the spectrum of the insertion loss has been used[3] but the method used can lead to inconsistent results. This inconsistency is now examined.

Consider the ⅓-octave-band sound pressure level measurements shown in Table A-1. The data were collected with the sound meter inside a vehicle, a Civic, with a Lincoln MKZ horn acting as the source (L_{P2}) and in the absence of the Civic in open air (L_{P1}). The overall levels for the two sets of data, meter inside the vehicle and the meter in the same location without the vehicle, can be calculated from the filtered data using the equation[23]:

$$L_P = 10 \log \sum_f 10^{L_{Pf}/10} \qquad \text{(A-2)}$$

where f represents the center frequency of a filter band. These overall levels are L_{P1} = 98.2 dBA and L_{P2} = 64.3 dBA without and with the Civic, respectively. Using Eq A-1 with these values, the insertion loss is 33.9 dBA.

Another approach to calculating insertion loss[3], which has the added benefit of providing an insertion loss spectrum, is to subtract the ⅓-octave-band sound pressure levels:

$$\Delta_f = L_{1f} - L_{2f} \tag{A-3}$$

The spectral differences can then be used with Eq A-2 to calculate the overall level of the differences of the ⅓-octave-band sound pressure levels. Again using the data for the Civic, this approach yields an insertion loss of 53.0 dBA. Thus an inconsistency exists in the value of the insertion loss depending on the manner in which it is computed using the ⅓-octave-band data. This inconsistency can be explained.

Combining Eq A-2 with the definition of insertion loss, Eq A-1, yields the following:

$$IL_{OVL} = L_{P1} - L_{P2} = 10\log\left(\frac{\sum_f 10^{L_{1f}/10}}{\sum_f 10^{L_{2f}/10}}\right) \tag{A-4}$$

Equation A-4 is an expression for the insertion loss based on two sets of ⅓-octave-band measurements that gives the same value as direct subtraction of L_{P2} from L_{P1}.

Now consider the algorithm used to compute the insertion loss based on the differences of the ⅓-octave-band values. Again, Eq A-1 is used and can be written as:

$$IL_{\Delta f} = 10\log\left(\sum_f \frac{10^{L_{1f}/10}}{10^{L_{2f}/10}}\right) \tag{A-5}$$

Comparison of Eqs A-4 and A-5 shows that the difference in the resulting value of the insertion loss stems from the fact that the difference of the logarithms is not the same as the logarithm of the differences.

Consider the *i*-th term of the argument of each of the logarithms of Eq A-4 and A-5, that is for $f = f_i$. It can be seen that

$$\frac{10^{L_{1f}/10}}{\sum_f 10^{L_{2f}/10}} \le \frac{10^{L_{1f}/10}}{10^{L_{2f}/10}} \tag{A-6}$$

or that

$$IL_{OVL} \le IL_{\Delta f} \tag{A-7}$$

This shows that, except for the special case where all acoustical energy is contained in one spectral frequency band, insertion loss calculated by summing spectral differences will always exceed the true insertion loss.

Table A-1, Spectral Insertion Loss
MKZ horn, '02 Honda Civic

Frequency f, Hz	L_{1f} dBA	L_{2f} dBA	$\Delta_f = L_{1f} - L_{2f}$ dBA
9.8	0.0	0.0	0.0
12.4	0.0	0.0	0.0
15.6	0.0	0.0	0.0
19.7	6.8	3.7	3.1
24.8	9.4	6.1	3.3
31.3	13.9	9.3	4.6
39.4	18.6	18.8	0.0
49.6	26.0	24.0	2.0
62.5	25.5	19.2	6.3
78.7	32.9	21.9	9.0
99.2	21.5	35.9	14.4
125.0	33.3	19.4	13.9
157.5	34.2	21.5	12.7
198.4	33.8	23.0	10.8
250.0	37.8	25.9	11.8
315.0	44.5	31.7	12.7
396.9	77.4	57.6	19.8
500.0	82.6	53.9	28.7
630.0	63.6	33.4	30.2
793.8	90.9	48.9	42.0
1000.0	83.1	63.7	22.4
1259.9	88.7	54.1	34.6
1587.4	95.1	53.4	41.7
2000.0	82.1	46.8	35.3
2519.8	86.1	44.9	41.2
3174.8	84.0	43.8	40.2
4000.0	77.2	42.5	34.7
5039.7	76.1	31.0	45.1
6349.6	73.6	28.7	43.9
8000.0	67.1	24.1	43.1
10079.4	61.0	18.0	43.0
12699.2	55.2	11.9	43.3
16000.0	46.5	6.3	40.2
20158.7	36.8	1.6	35.3
Overall	98.2	64.3	53.0