the state transportation agencies and would add reliability to the predictions of the model nationwide. Verification of the emission level data will not only give the user more confidence in his analysis, but it also has the potential for providing more cost-effective noise barrier designs.

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Rumble Strip Noise

JOHN S. HIGGINS and WILLIAM BARBEL

ABSTRACT

The Illinois Department of Transportation (IDOT) placed rumble strips near the north end of the Edens Expressway to alert drivers that they were approaching a signalized intersection. The intersection was a high-accident location, and previous safety measures were not significantly effective in lowering the number or severity of the accidents. Many complaints about noise were received from adjacent property owners after the strips were placed. When a berm that was placed between the residents and the strips did not reduce the complaints, IDOT requested assistance from the Demonstration Projects Division of FHWA to study berm effectiveness and rumble strip noise. Two types of strip construction were compared, the formed and the cut types. Several different configurations were also analyzed. Outside measurements were taken at three sites, and inside noise measurements were taken from the tractor of a semitrailer unit. Vibration measurements were taken from the steering column of the truck. The results indicated that the formed type of strip provided better driver perception than did the cut type at all speeds tested. Outside noise did not significantly vary with the different types and configurations of the rumble strips. The strips appear to have reduced the number and severity of accidents at the Edens Expressway location.

Rumble strips have been used by highway agencies as a safety feature to alert drivers to some impending change in the traffic flow (i.e., an upcoming toll booth on an expressway, and construction zones). Typically, the strips are used in conjunction with a visual stimuli, such as warning signs or lights. When the strips are crossed over, a driver feels the vibration and hears the noise. This causes the driver to become more alert and, on seeing the visual stimuli, to take the appropriate action.

The strips are usually made by cutting, or forming, transverse grooves or ridges in the pavement approximately 1 to 2 cm (0.5 to 1 in.) deep. The width, distance between, and the number of grooves (or ridges) vary. A set of grooves or ridges becomes a rumble strip. Typically, three strips are used with a length of untreated pavement in between each strip.

The Illinois Department of Transportation (IDOT) placed a set of rumble strips to warn drivers of the terminis of the Edens Expressway at Clavey Road in Highland Park. This intersection, which is signalized, has a high-accident history, the most severe being rear-end collisions. The abrupt change from a limited-access facility to a major arterial was the cause of these accidents. IDOT had tried several improvements to alleviate the problem, such as signs and warning lights. The effectiveness of these improvements has not been significant (1).

Public pressure became so great that rumble strips were placed to help warn the drivers of the upcoming signal. Immediately, complaints about noise from the rumble strips were received from the neighboring homeowners. IDOT attempted to reduce the noise from the rumble strips by constructing a 3.2-m

(10-ft) berm. When the complaints continued, IDOT requested assistance from the Demonstration Projects Division of FHWA in analyzing the noise being generated from the rumble strips and the effectiveness of the berm.

Another problem that IDOT wished to investigate was the vibration inside the vehicle as it passed over the rumble strip. IDOT testing indicated that the vibration inside automobiles was felt, but in large trucks it was not noticeable.

THE STUDY

The study had three objectives:

1. To measure the noise amplitude and frequency of the strip at various distances from the highway,
2. To measure the vibration inside a semitrailer tractor as it passes over the strips, and
3. To analyze how selected strip configurations affect both outside and inside vehicle noise and vibration when the tractor passes over it.

SITE DESCRIPTION

At the first three sites noise and vibration were analyzed from existing rumble strips. At the fourth site strips with different configurations were temporarily placed for analysis.

1. Site 1, East-West Toll Road at Toll Plaza No. 61: The strips are located in concrete pavement on the westbound lanes. Figure 1 shows the general configuration, and Table 1 gives the specific dimensions of the strips. Note that the grooves are rounded, which eliminate any sharp edges. The terrain slopes gradually upward from the roadway. These strips are of the formed type.
2. Site 2, Edens Expressway at Clavey Road: The strips are located in the northbound lanes, and their configuration is shown in Figure 2 (the dimensions are given in Table 1). These grooves were cut into the concrete pavement. Note that these strips have sharp edges rather than the rounded ones at Site 1. A 3.2-m-high (10-ft) berm separates the roadway and the neighboring property owners.
3. Site 3, US-12, south of Volo, Illinois: Four sets of strips, each with a different configuration, were cut into the concrete in the southbound lanes. The general configurations are shown in Figure 2, and the specific dimensions are given in Table 1. Note that strip A has a 10-degree tilt from normal. The terrain near the highway was generally flat, open fields.
4. Site 4, Tri-State Tollway at Toll Plaza No. 21: This site is similar to Site 1, only the grooves are slightly deeper and have been filled with a small lift of asphalt. (Refer to Figure 1 and Table 1 for the dimensions.) Only internal truck vibration and noise measurements were taken at this site.

Outside measurements were taken by using up to eight microphones, a real-time analyzer, and a computer (equipment from FHWA Demonstration Project No.

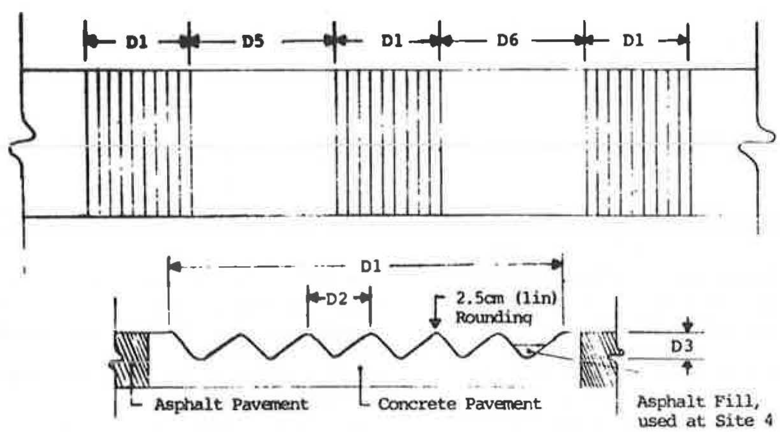

FIGURE 1 Strip layout: Site 1, East-West Toll Road, and Site 4, Tri-State Tollway.

TABLE 1 Rumble Strip Dimensions

Site	Length of One Strip, D1 (m)	Type of Strip	No.	Center-to-Center Distance of Grooves, D2 (cm)	Depth, D3 (cm)	Width, D4 (cm)	Distance Between Strips (m) 1-2 (D5)	2-3 (D6)
1	6.4	Formed[a]	42	15	0.8	NA	32.2	29.4
2	6.1	Cut	21	32	1.6	10	30	30
3								
Strip A	3.6	Cut[b]	13	30.5	1.3	10	30[c]	
Strip B	3.6	Cut	13	30.5	1.9	10	30	
Strip C	6.1	Cut	21	30.5	1.3	10	30	
Strip D	2.4	Cut	13	20.3	1.3	10	30	
4	6.4	Formed[d]	42	15	1.7	NA	29.5	30.8

Note: 1 m = 3.28 ft, 1 cm = 0.39 in., and NA = not applicable.

[a]Grooves formed with 2.5-cm rounding, thus eliminating all sharp edges.

[b]Grooves cut on a 10-degree tilt, thus creating a 0.6-m offset from one end to the other.

[c]Only two strips were cut.

[d]Grooves similar to those at Site 1; however, an asphalt lift was used in the groove to flatten the bottom.

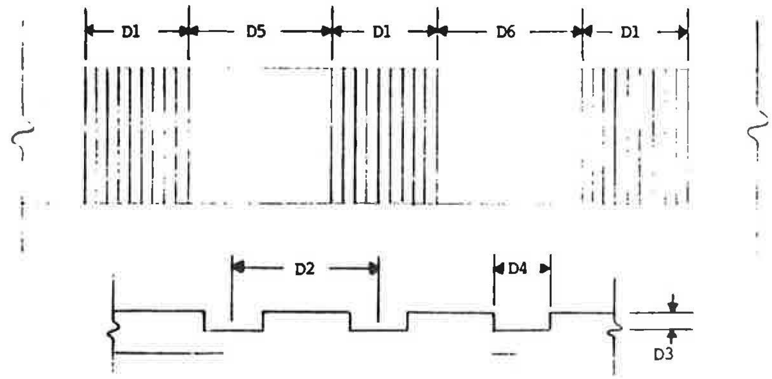

FIGURE 2 Strip layout: Site 2, Edens Expressway, and Site 3, US-12.

45, Highway Noise Analysis). Simultaneous measurements were taken at all microphones, with a sampling rate of 0.125 sec. A frequency distribution was obtained from various microphones at each site. Several measurement periods, each 15 min long, were conducted at Sites 1 and 2. A 1-min period was used at Site 3.

A Digital Acoustics 607 portable sound analyzer recorded the peak noise levels from vehicles crossing the center rumble strip. The duration greater than a threshold value of 75 dB(A) was also recorded.

MICROPHONE PLACEMENT

At Site 1 three microphones [channels (Ch) 43, 46, 47] were placed 15 m (50 ft) from the centers of the three strips. Another was placed as far as possible from the strips, while still maintaining the 15-m distance from the roadway (Ch 42). Three other microphones (Ch 44, 45, 48) were placed at various distances from the center strip in an attempt to measure the drop-off rate. The 607 was placed 15 m from the center strip (near Ch 47). Figure 3 shows the layout of the site. Traffic volumes and speeds were recorded for each vehicle classification (i.e., cars).

At Site 2 the microphones were placed to measure the barrier insertion loss at various locations on the neighboring properties (Ch 42, 44, 46). Measurements were taken in the bedrooms of two of the affected homes (Ch 45, 49), with the windows open and closed. Frequency measurements were obtained from the top of the berm (Ch 43), in the backyard (Ch 44), and in the bedroom (Ch 45, windows open) of house 226. A microphone (Ch 47) was placed in the front yard of house 242 to measure the neighborhood noise levels. Figure 4 shows the layout of the site. Traffic volumes and speed were also measured at this site.

At Site 3 microphones were placed 15 m from the center of each set of rumble strips (Ch 42, 43 for strips A and C; Ch 46, 47 for strips B and D). Microphones were also placed at various distances away from the highway to measure the drop-off rate (Ch 44, 45 for strips A and C, Ch 48, 49 for strips B and D). Frequency distributions were obtained from the microphones 15 m away from the strips (Ch 43, 46). The 607 was placed 15 m from the center of strips A and C only (near Ch 43). The only noise measured at this site was from the test semitrailer traveling at speeds of 56, 65, 73, 81, and 88 km/h (35, 40, 45, 50, and 55 mph), and a automobile at speeds of 56, 73, and 88 km/h (35, 45, and 55 mph) only. Figure 5 shows the layout of the site, and microphone placement at the strips is given in Table 2.

MEASUREMENT AND PREDICTION PROCEDURES

Outside measurements were conducted in accordance with the guidelines set forth in an FHWA report (2). Both FHWA noise prediction models (STAMINA 1.0 and STAMINA 2.0) (3,4) were used to obtain predicted

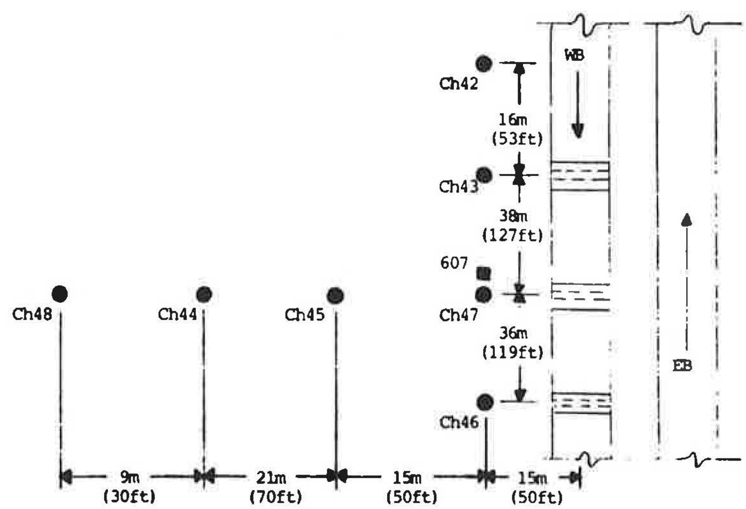

FIGURE 3 Site 1 microphone placement.

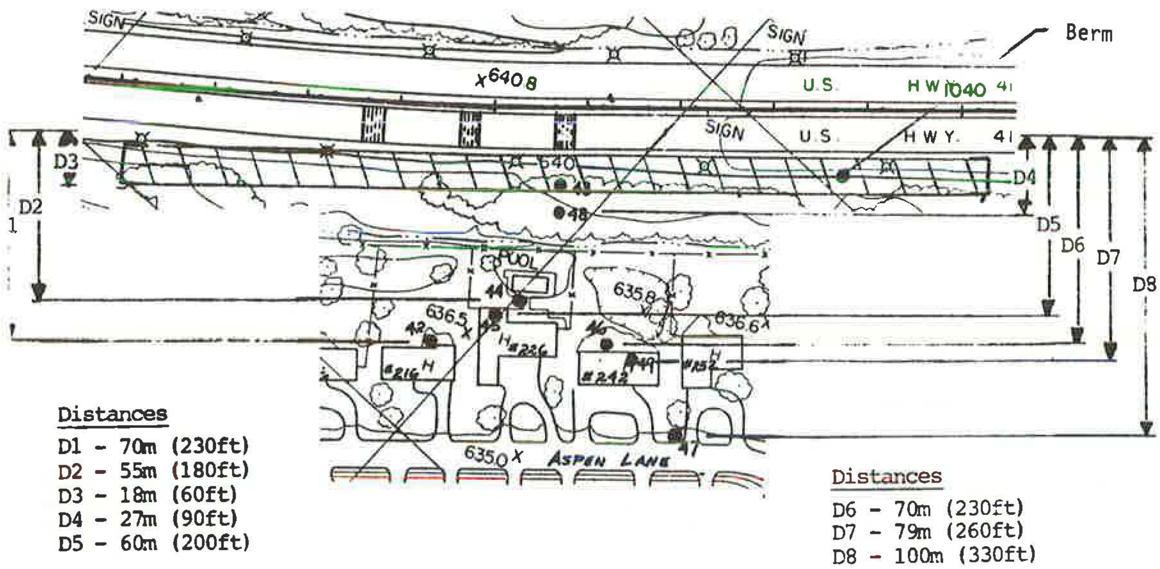

FIGURE 4 Site 2 microphone placement.

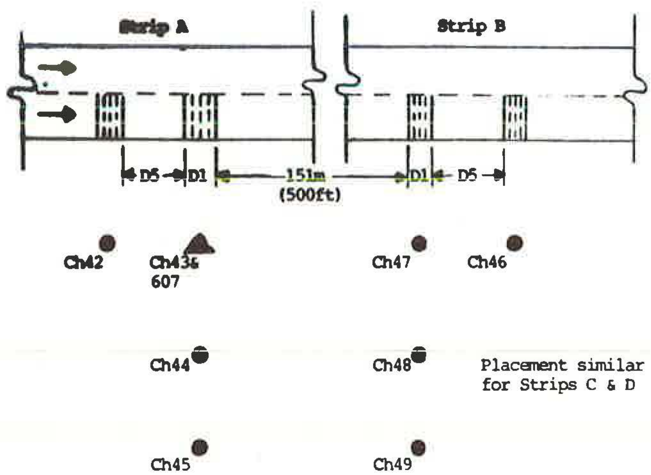

FIGURE 5 Site 3 microphone placement.

TABLE 2 Microphone Locations for Site 3

	Distance (m) From Center of Rumble Strip by Channel							
Strip	42	43	44	45	46	47	48	49
A	15	15	45	90[a]	-	-	-	-
D					15	15	45	79[b]
C	15	15	45	75[a,b]	-	-	-	-
D	-	-	-	-	15	15	45	105

Note: 1 m = 3.28 ft.
[a]Offset slightly because of electrical interference.
[b]Maximum cable length reached.

sound levels and frequency distributions at each microphone location from traffic traveling on normal pavement conditions. The predicted values provide a comparison between the expected no-rumble strip condition and the rumble strip condition at each site. The models were used only at Sites 1 and 2.

Internal noise measurements were done by using a B&K impulse sound level meter. Vibrations from the steering column were obtained by using a B&K accelerometer. The vehicle steering column was chosen to measure the vibration because of the direct vibration transmission from the tires, through the steering assembly, to the driver's hands. Data were recorded on a B&K FM data tape recorder. Speeds for which the noise and vibration data were taken at were 56, 65, 73, 81, and 88 km/h (35, 40, 45, 50, and 55 mph). Data were only taken up to 73 km/h (45 mph) at Site 2 because the speed limit was 65 km/h (40 mph). Data were analyzed by running the data through a B&K narrow band fast Fourier transformation (FFT) analyzer and HP chart recorder. Vibration charts were plotted by using millivolts versus frequency (hertz). Internal noise measurements were expressed in sound level [dB(A)] versus frequency (hertz).

To obtain driver perception of the vibration caused by passing over the strip, the vibration from the pavement just before going over the rumble strip was compared with that when the vehicle was on the strip. The frequency of most concern is 2 to 5 Hz, because it is the most sensitive for passenger comfort. Most vehicle suspension systems are designed to resonate at frequencies slightly higher--5 to 20 Hz (5,6).

RESULTS

Site 1, East-West Toll Road

Although three measurement periods were conducted, only two periods of data are available because of an overflow during one period. The noise levels for each channel are shown in Figure 6. The noise levels at each location are similar between the two periods. The L_{eq} at the 15-m (50-ft) microphones (Ch 43, 46, 47) was 78 dB(A), with peak noise levels ranging from 84 to 114 dB(A). The duration above the threshold level ranged from 0.5 to 2 sec. The average peak level was 90 dB(A), which lasted for 0.75 sec. The L_{eq} at the microphone placed near the untreated pavement (Ch 42) was 3 to 4 dB(A) lower than those near the strips.

The frequency distribution from 15 m away from the center strip (Ch 47) is shown in Figure 7. The A-weighted noise level is shown by the bar and numerical value next to 8-A. The bars and numerical values next to lines 14-40 show the distribution of the noise for each frequency band. In both periods the dominant frequencies were in the 80 to 160 Hz

PERIOD NO. 1

CHANNEL NO	I	LEQ	L_1	L_5	L_{10}	L_{50}	L_{90}	L_{99}
42	I	75.7	80.0	83.0	79.0	66.0	56.0	53.0
43	I	79.7	92.0	87.0	81.0	66.0	56.0	53.0
44	I	63.9	75.0	70.0	68.0	50.0	52.0	50.0
45	I	69.0	80.0	76.0	73.0	61.0	56.0	54.0
46	I	70.8	91.0	86.0	82.0	67.0	57.0	53.0
47	I	70.6	91.0	86.0	82.0	66.0	56.0	53.0
48	I	61.7	72.0	68.0	65.0	57.0	50.0	50.0

PERIOD NO. 2

CHANNEL NO	I	LEQ	L_1	L_5	L_{10}	L_{50}	L_{90}	L_{99}
42	I	74.7	87.0	82.0	77.0	64.0	55.0	51.0
43	I	70.4	92.0	85.0	70.0	65.0	55.0	52.0
44	I	63.1	75.0	70.0	66.0	57.0	51.0	50.0
45	I	68.2	80.0	75.0	72.0	60.0	56.0	55.0
46	I	77.6	91.0	85.0	80.0	65.0	56.0	53.0
47	I	77.3	90.0	84.0	80.0	64.0	55.0	52.0
48	I	61.2	73.0	67.0	64.0	55.0	50.0	50.0

FIGURE 6 Noise levels at Site 1.

and 315 Hz ranges. The fundamental frequency was calculated to be 161 Hz at 88 km/h (55 mph). The measured values show the fundamental frequencies as well as the harmonics.

The STAMINA 1.0 model predicted noise levels, with normal pavement, of 2 to 6 dB(A) less than the measured values. The dominant frequency range was computed to be 500 to 1,000 Hz, which was considerably higher than the measured values.

Inside the test truck, peak noise levels ranged from 75 to 92 dB(A), depending on the speed when the truck passed over the strips; the average value was 87 dB(A). The fundamental frequency was seen in both the interior noise levels and the vibration when the truck passed over the first set of grooves. A significant difference in the vibration displacement amplitude, in the 1 to 20 Hz range, was measured between the pavement just before the rumble strip and when the truck was passing over the strip. Figure 8 (6) presents this difference for the truck at 65 km/h (40 mph). A similar difference was found for all speeds tested.

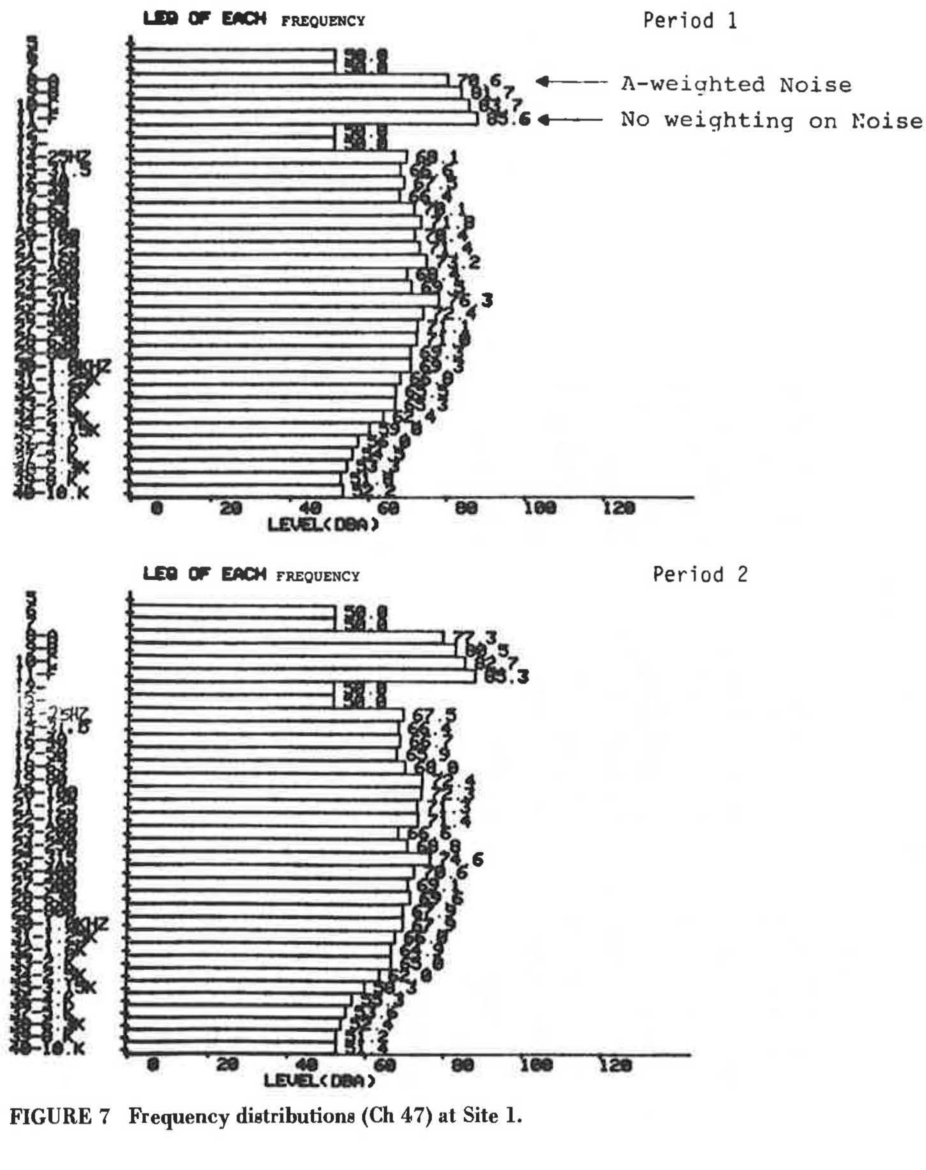

FIGURE 7 Frequency distributions (Ch 47) at Site 1.

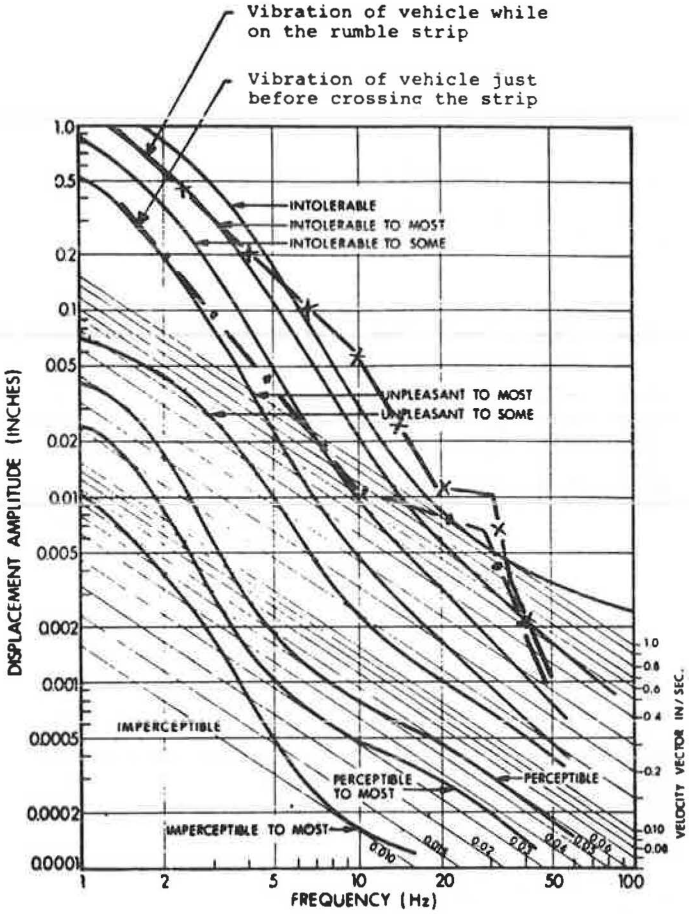

FIGURE 8 Vehicle vibration at Site 1 at 65 km/h (40 mph) *(6)*.

PERIOD NO. 1

CHANNEL NO	I	LEQ	L_1	L_5	L_{10}	L_{50}	L_{90}	L_{99}	
42	I	61.7	67.0	66.0	65.0	61.0	56.0	54.0	
43	I	79.0	88.0	85.0	83.0	75.0	68.0	63.0	
44	I	61.6	67.0	65.0	64.0	61.0	58.0	56.0	
45	I	50.0	50.0	50.0	50.0	50.0	50.0	50.0	Windows closed
46	I	61.7	69.0	65.0	64.0	60.0	57.0	55.0	
47	I	58.7	64.0	61.0	60.0	58.0	56.0	55.0	
48	I	59.5	67.0	64.0	62.0	58.0	52.0	50.0	
49	I	50.0	50.0	50.0	50.0	50.0	50.0	50.0	Windows closed

PERIOD NO. 2

CHANNEL NO.	I	LEQ	L_1	L_5	L_{10}	L_{50}	L_{90}	L_{99}	
42	I	62.1	68.0	66.0	65.0	61.0	57.0	54.0	
43	I	79.0	87.0	85.0	83.0	76.0	68.0	59.0	
44	I	62.1	68.0	66.0	64.0	61.0	58.0	56.0	
45	I	56.7	62.0	59.0	58.0	56.0	55.0	54.0	Windows Open
46	I	61.8	68.0	65.0	64.0	61.0	57.0	55.0	
47	I	60.9	68.0	64.0	62.0	58.0	56.0	55.0	
48	I	59.7	67.0	64.0	63.0	58.0	53.0	50.0	
49	I	54.2	59.0	58.0	57.0	53.0	50.0	50.0	Windows Open

PERIOD NO. 3

CHANNEL NO.	I	LEQ	L_1	L_5	L_{10}	L_{50}	L_{90}	L_{99}	
42	I	61.9	67.0	66.0	65.0	61.0	57.0	55.0	
43	I	79.2	88.0	85.0	83.0	76.0	68.0	61.0	
44	I	61.7	66.0	65.0	64.0	61.0	57.0	55.0	
45	I	57.3	62.0	59.0	58.0	56.0	54.0	53.0	Windows Open
46	I	61.6	66.0	65.0	64.0	61.0	57.0	55.0	
47	I	61.5	67.0	62.0	61.0	59.0	57.0	56.0	
48	I	59.1	65.0	63.0	62.0	58.0	52.0	50.0	
49	I	54.6	60.0	58.0	57.0	54.0	50.0	50.0	Windows Open

FIGURE 9 Noise levels at Site 2.

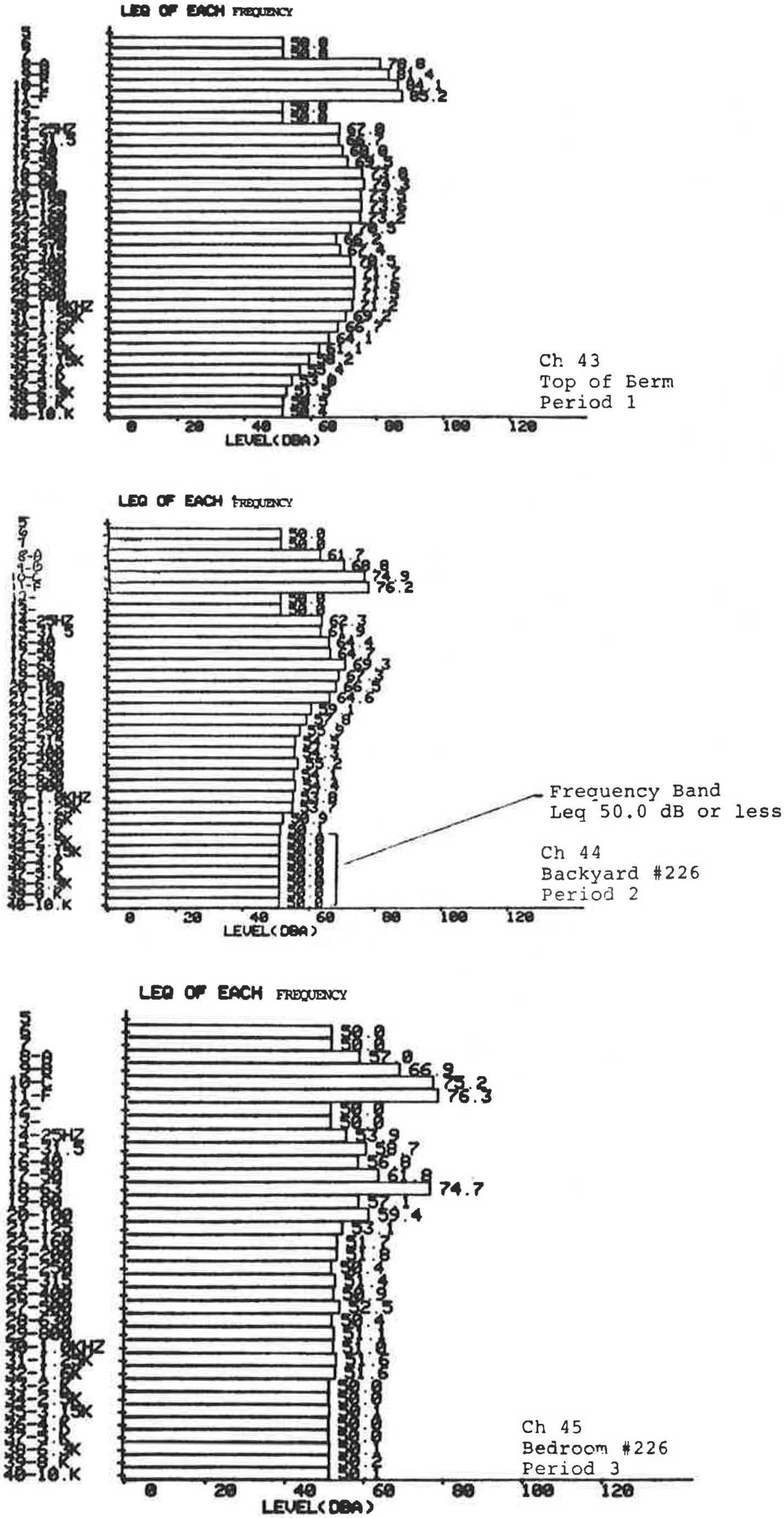

FIGURE 10 Frequency distributions at Site 2.

Site 2, Edens Expressway

Three measurement periods were successfully completed at Site 2. The noise levels at each location were consistent over the three periods; they are shown in Figure 9. The measured L_{eq} in the backyards (Ch 42, 44, 46) was in the low 60s. In the bedrooms (Ch 45, 49) with the windows opened the L_{eq} was in the high 50s; with the windows closed the L_{eq} was less than 50 dB(A). By using the FHWA procedure (2), the berm insertion loss was computed at 10 dB(A), which agrees well with computations by IDOT and an independent consultant.

The frequency measured on top of the berm (Ch 43) was in the ranges of 63 to 160 Hz and 500 to 1,000 Hz. In the backyard (Ch 44) the berm effectively reduced the high frequency noise but did little to the lower frequency noise. In the bedroom (Ch 45, windows open), the low frequency noise was the most significant contributor (75 dB). Taking into account the A-weighted scale, the noise would be 50 dB(A), enough to disturb a person sleeping. Figure 10 shows the frequency distribution at the three locations.

The STAMINA 1.0 model predicted noise levels, with normal pavement, of 2 to 7 dB(A) less than were measured, with the majority of the noise occurring in the 250, 500, and 1,000 Hz octave bands.

Inside the semitrailer the peak noise ranged from 80 to 86 dB(A). The fundamental frequency that was calculated for this set of strips ranged from 53 to 84 Hz, depending on vehicle speed. Many harmonics were created as the vehicle passed over the strips, but they were not as distinct as those created by the strips at Site 1. The vibration created by the pavement just before the strips was similar to that found while on the strips. There was not a significant change in the displacement amplitude between the two in the 1 to 20 Hz range for the speeds tested. Figure 11 (6) shows this difference for the truck at 65 km/h (40 mph).

Site 3, US-12

All outside measurements were completed satisfactorily. No inside vibration or peak noise levels were available because of an equipment malfunction. The peak noise levels measured from the truck (Ch 42, 43, 46, 47) ranged from 78 to 84 dB(A), depending on speed. Figure 12 shows the average peak noise levels from the semitrailer at 15 and 45 m (50 and 150 ft) from the rumble strips. The average peak noise levels measured by the 607 were approximately 1 to 2 dB(A) higher than those measured by the computer and had an average duration above the threshold [75 dB(A)] of 2 sec. The test automobile had peak noise levels about 3 dB(A) less than those of the truck, and the duration greater than the threshold was about 0.5 sec.

Frequency measurements were conducted on strips A and C. The dominant frequency range at strip A was measured in the 63 to 84 Hz range, depending on vehicle speed. The calculated fundamental frequency ranged from 50 to 80 Hz. The dominant frequency range at strip C was measured in the 50 to 100 Hz range, depending on vehicle speed. The calculated

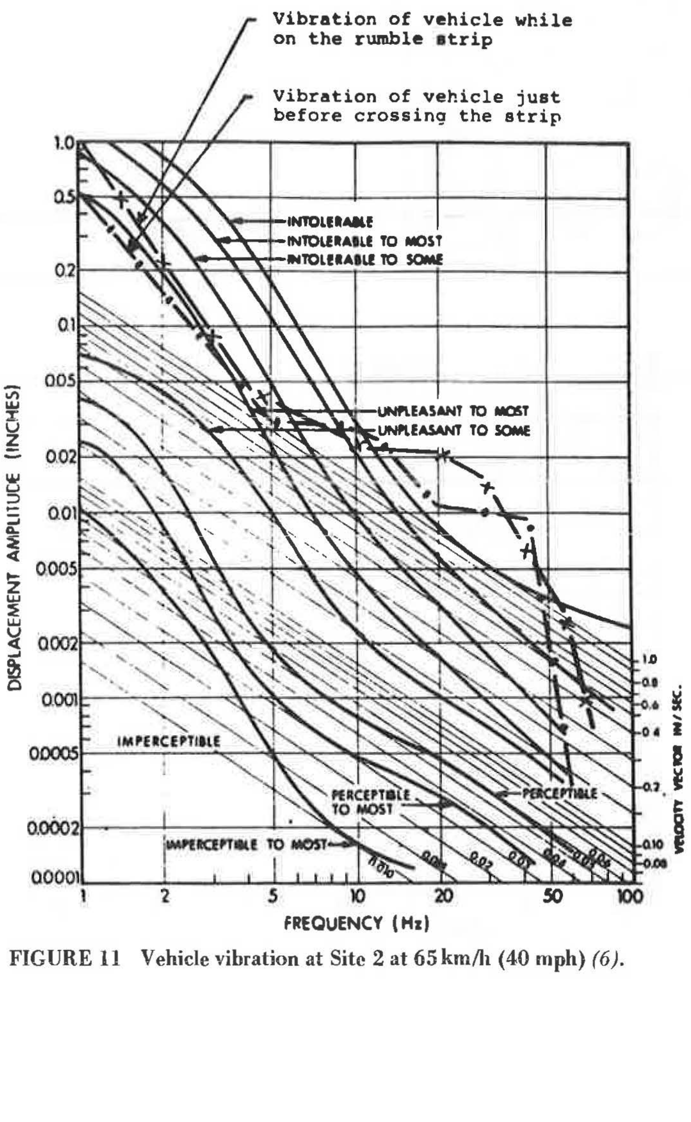

FIGURE 11 Vehicle vibration at Site 2 at 65 km/h (40 mph) *(6)*.

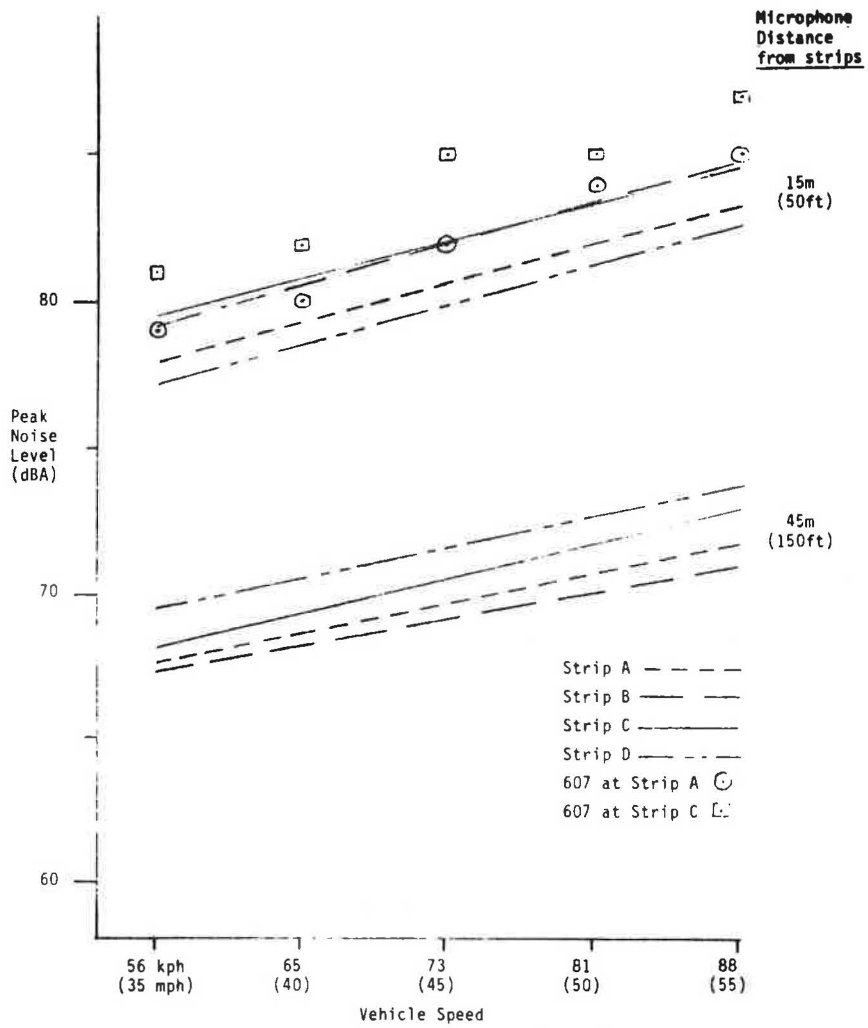

FIGURE 12 Average peak noise levels at Site 3.

fundamental frequency range is the same as that for strip A.

Although the inside equipment malfunctioned, the record level meter settings and the subjective responses from the driver and passengers indicated that strip C produced significant driver perception at the lower speeds tested [56, 65, and 74 km/h (35, 40, and 45 mph)], and strip D produced significant perception at the higher speeds tested [80 and 88 km/h (50 and 55 mph)].

SUMMARY AND CONCLUSIONS

Although this study was limited, enough information was obtained to establish that rumble strips create a noise that is different from normal traffic noise. Because of this, the highway designer should be aware of strip placement when near a residential area.

The following is a list of other conclusions reached in this study.

1. A rumble strip produces a low frequency noise that can increase the L_{eq} noise levels by up to 6 or 7 dB(A) over noise levels produced by traffic on normal pavement.
2. A berm can significantly reduce high frequency noise, but it is not effective in reducing low frequency noise, such as that produced by a vehicle passing over a rumble strip.
3. A rumble strip that is formed rather than cut into the pavement creates better driver perception.
4. The groove center-to-center distance has some effect on driver perception. Smaller center-to-center distances appear to be more effective on vehicles traveling at higher speeds.
5. The outside noise, which adjacent property owners will hear, does not significantly vary with strip configuration.
6. The outside noise created by an automobile passing over a strip is slightly less than that created by a truck passby. The duration of the noise is much shorter than the duration of a truck.
7. The addition of rumble strips on the Edens Expressway appears to have reduced the number and severity of accidents.

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Examination of the Dependence of Diesel-Electric Locomotive Noise Emission on Speed, Rated Power, and Age

ERIC STUSNICK

ABSTRACT

A statistical analysis was conducted of an FRA data base of locomotive passby noise levels to determine the dependence of diesel-electric locomotive noise emission on speed, rated power, and age. Although a statistically significant dependence on locomotive speed was determined, the data set did not indicate a significant dependence on rated horsepower or age. Reasons for this finding are discussed.

Federal noise emission standards for moving locomotives in line-haul service limit the maximum A-weighted passby sound level at 100 ft to 96 dB for locomotives manufactured before December 31, 1979, and to 90 dB for locomotives manufactured after that date (40 CFR Part 201). Most existing locomotives meet this standard.

Recent efforts to improve fuel economy are leading the diesel-electric locomotive manufacturing industry to design diesel engines with higher rated power than is currently used. There is some concern that locomotives with such engines will not be able to meet the federal noise emission standard. At the time of the development of the noise emission standards, fuel economy was not an important issue.

In addition, there is concern that the noise emissions of a diesel-electric locomotive may increase as the unit ages. If this occurs, then a locomotive that just meets the standard when new may not meet the standard when older.

In order to put some of these concerns in perspective, a study was carried out to examine the dependence of diesel-electric locomotive noise emission on locomotive speed, rated power, and age.

SOUND LEVEL AS A FUNCTION OF SPEED

The data base used in this study was a computerized listing of locomotive passby sound levels measured by the Office of Safety of the FRA during the period from September 1978 to June 1981. It contained measurements of maximum A-weighted sound levels at 100 ft for 379 single- and multiple-locomotive passbys. Figure 1 shows the distribution of sound levels, which ranged from 69 to 97 dB (1).

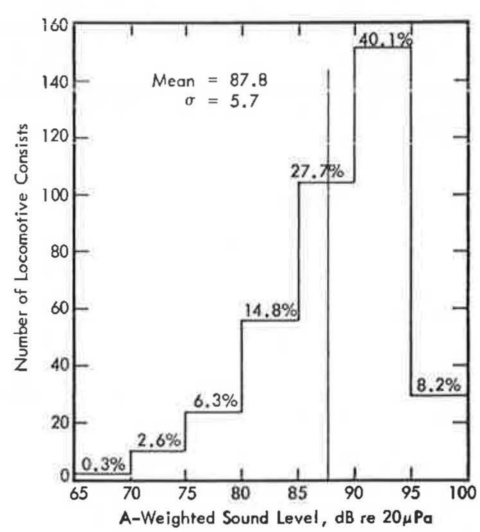

FIGURE 1 Distribution of sound levels for moving locomotive consists.