Heavy-Truck Noise Emission Levels on Grades in California

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ABSTRACT

As part of a federally funded research project to update vehicle noise emission levels, the California Department of Transportation (Caltrans) examined heavy-truck noise emission levels on grades in California. Nearly 1,800 noise measurements were taken at 6 locations along Interstate and state freeways with grades ranging from +3 to +7 percent. The six sites were located far enough upgrade to allow heavy trucks to decelerate from free-flowing speeds of 55 to 60 mph to sustained crawl speeds before measurement. The noise data showed no direct grade dependency at any observed speed. This may have been caused by the inverse relationship between grade steepness and truck weight for a given speed. In order to maintain the same crawl speeds, trucks must be carrying lighter loads on steeper grades, and vice versa, possibly resulting in offsetting effects on noise emission levels. Further research into the exact cause is recommended. Speed dependency, however, was significant. A second-degree polynomial equation for noise energy versus $\log_{10}$ speed was found to represent the best curve fit. A combined speed-dependent curve for +3 to +7 percent grades was developed. Observed speed distributions were found to be grade dependent and appeared to agree with those typically found for trucks on grades in California. This information was used to develop "default" reference energy mean emission levels for heavy trucks on grades up to +7 percent in 1-percent increments. For 3 to 5 percent grades, these values are 1.4 to 0.5 dBA higher than those developed by the currently used NCHRP 117 method; above 5 percent grade the default values are 0.2 to 2.1 dBA lower than those of NCHRP 117.

This study was part of a federally funded research project to measure vehicle noise levels and develop speed-dependent reference energy mean noise emission levels for highway traffic noise prediction models in California. The California vehicle noise (Calveno) reference energy mean emission levels for level roads were developed, published (1), and approved by FHWA for noise studies involving federal-aid highway projects. They conform with the requirements set forth by the Federal-Aid Highway Program Manual (2). In March 1985, the Calveno curves were implemented for use by the California Department of Transportation (Caltrans) in traffic noise studies.

During the study of level-road noise emissions, a limited amount of noise measurements was made on three different uphill grades. Preliminary analysis of these grade data strongly suggested that the recommended procedures for grade corrections in Report FHWA-RD-77-108 (3) are not correct. An extension to the research project was requested by Caltrans and subsequently approved by FHWA. The objectives of the extension were to include heavy-truck noise emission levels on grades up to 7 percent.

For the sake of consistency with the level-road study, heavy trucks were defined as trucks with three or more axles. This definition is also consistent with the definition stated in Report FHWA-RD-77-108 (3).

Because of observed extremes in noise emissions of trucks traveling downhill due to variations in downshifting and braking, the study was limited to heavy trucks traveling uphill at sustained crawl speeds only.

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SITES

With the obvious exception of level-road requirements, all noise measurement sites conformed with the criteria listed in Reports FHWA-OEP/HEV-78-1 (4) and FHWA-DP-45-1R (5). The site criteria used throughout this research project are discussed in detail in the report California Vehicle Noise Emission Levels (1).

All grade sites consisted of compacted, graded dirt emergency turnouts. They were judged to have acoustical site characteristics of somewhat less reflectivity than the hard sites defined in the FHWA report (3). The sites were carefully selected to reduce variability caused by topography, acoustical absorptivity and reflectivity, and source characteristics such as heavy-truck populations, pavement type, and condition. Six sites were selected, ranging in grade from +3 to +7 percent.

All grade sites were located along major Interstate or state freeways. Trucks and other traffic moved at free-flowing speeds averaging 55 to 60 mph on level-roadway stretches before beginning their ascent. The sites were located far enough uphill to allow truck speeds to decelerate to sustained crawl speeds. The distances from the bottom of the grades to the sites varied from a minimum of 1 mi for the +7 percent grade to 1.5 mi for the +3 percent grade. According to a Caltrans report, these distances were long enough to ensure deceleration of trucks to a constant crawl speed (6). There were no other constraints on traffic movement, such as merging of

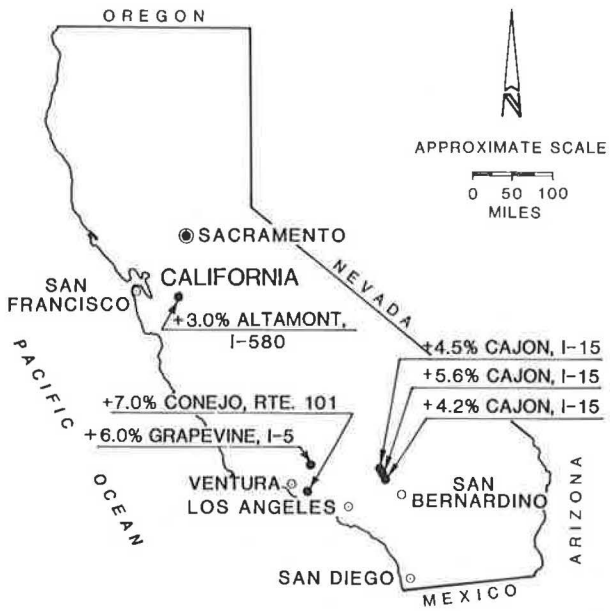


FIGURE 1 Locations of noise measurement sites.

traffic, speed limits of less than 55 mph, or roadway construction.

Following is a brief listing of the sites, including percent of grade, name of grade, route number, and general location:

- +3.0 percent, Altamont Pass, eastbound I-580 east of Livermore;
- +4.2 percent, Cajon Pass, northbound I-15 north of San Bernardino;
- +4.5 percent, Cajon Pass, northbound I-15 north of San Bernardino;
- +5.6 percent, Cajon Pass, northbound I-15 north of San Bernardino;
- 6.0 percent, Grapevine, southbound I-5 north of Los Angeles; and
- +7.0 percent, Conejo, southbound Route 101 southeast of Ventura.

Figure 1 shows the site locations.

INSTRUMENTATION

All sound level meters (SLMs) used in this study were Type 1 Precision SLMs as specified by the American National Standards Institute (ANSI S1.4, 1983). They were connected to a data logger specifically designed for the Caltrans Transportation Laboratory. This instrument has 16 channels that may be selectively activated to receive up to 16 dc output signals from the SLMs. A microprocessor in the data logger transforms the continuous, time-varying electrical signals into digital form and calculates a variety of noise descriptors, including the maximum noise level. The latter feature was useful in determining the maximum passby noise levels of heavy trucks.

Figure 2 shows the typical instrumentation setup used at four of the six sites: +3.0, +4.5, +6.0, and +7.0 percent grade. For logistical reasons, only one microphone was used at the two remaining sites (+4.2 and +5.6 percent grade). The three-microphone configuration was designed to detect any variations in acoustical results caused by site characteristics. This was accomplished by examining the noise attenuations between the 25-ft and 50-ft microphones.

Figure 3 shows the typical site layout for a three-microphone setup and clearance criteria. Except for the number of microphones, all site and instrumentation criteria and configurations were the same for the two setups employing one microphone. In all setups, the reference microphone was Microphone 2, 50 ft from the center line of the nearest lane. The microphone height at the reference location was 4 to 6 f ± 0.5 ft above the ground and 5 ft ± 0.5 ft above the plane of the pavement.

In addition to the data logger, the reference

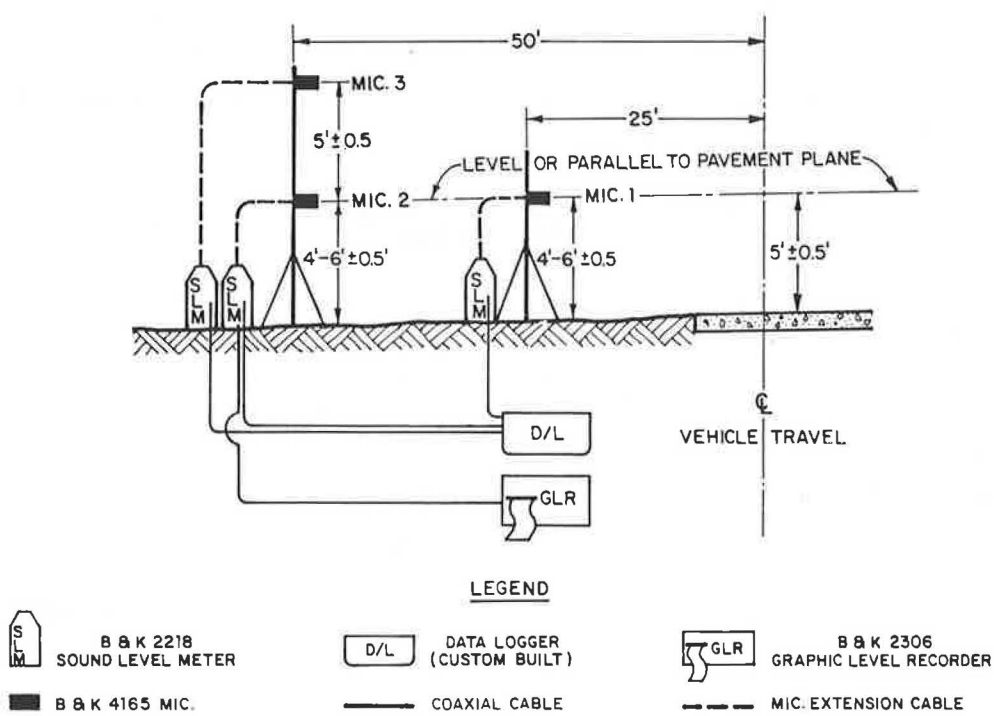


FIGURE 2 Typical setup for noise measurements.

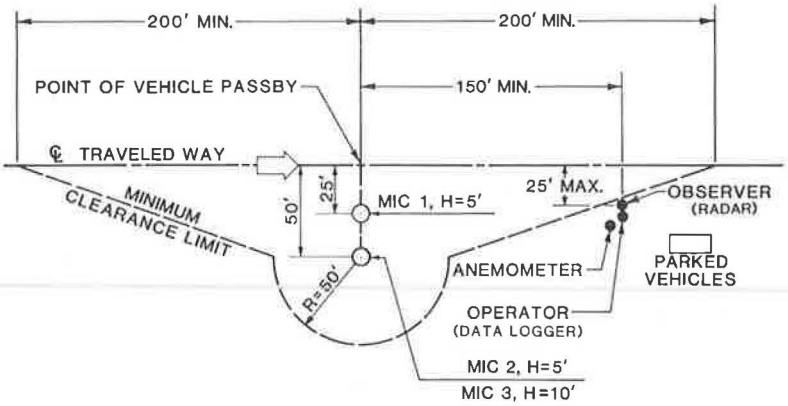


FIGURE 3 Typical site layout and microphone locations.

microphone was connected to a graphic level recorder. Its purpose was to determine whether truck noise peaks were significantly contaminated by other traffic or background noise.

FIELD MEASUREMENTS

The field measurements consisted of three types: truck speed, A-weighted noise, and meteorological. The first measurement operation was performed by a vehicle observer using a radar gun and the last two operations by an instrument operator. All measurement procedures and criteria were identical to those reported in California Vehicle Noise Emission Levels (1) and were consistent with Reports FHWA-OEP/HEV-78-1 (4) and FHWA-DP-45-1R (5). The meteorological measurements were made to ensure that the recommended windspeed and humidity criteria of 12 mph and 95 percent, respectively, were not exceeded.

Heavy-truck passby measurements were limited to those tracks traveling in the near lane. This did not appear to introduce a bias toward slower, heavier trucks. Most trucks, slow or fast, traveled in the near lane (outside lane) on grades. As will be seen later, observed speed distributions compared favorably with typical truck speeds observed in California on grades (6).

The vehicle observer began tracking the target truck with the radar gun approximately 400 ft before the point of passby (closest to the microphones). If the speed varied by more than 1 mph, the vehicle was assumed to be accelerating or decelerating, and the measurements was rejected.

In order to avoid significant contamination of the truck noise measurements without introducing a bias toward the noisier vehicles, a 6-dBA rise and fall in noise levels was considered the minimum acceptable, or valid, peak. This criterion was also used in the level-road study (1). A 10-dBA criterion would have been ideal from a contamination control standpoint but would possibly have created a bias toward noisier trucks.

Figure 4 presents the development of a criterion for minimum vehicle separation, assuming equal noise sources and a background noise level of 10 dBA lower than the peak at the point of passby. The minimum distance between two trucks was calculated as 308 ft in order to limit contamination to 0.5 dBA. Note that the valley between the two peaks is 6 dBA and conforms to the 6-dBA rise-fall criterion mentioned earlier. Because of uncertainties in the foregoing assumptions, the minimum separation between two trucks was kept at 400 ft.

Other valid peak scenarios are presented in Figure 5 with the possible amounts of contamination. To keep track of the possible contaminated measurements, graphic level recorder (GLR) traces from the refer-

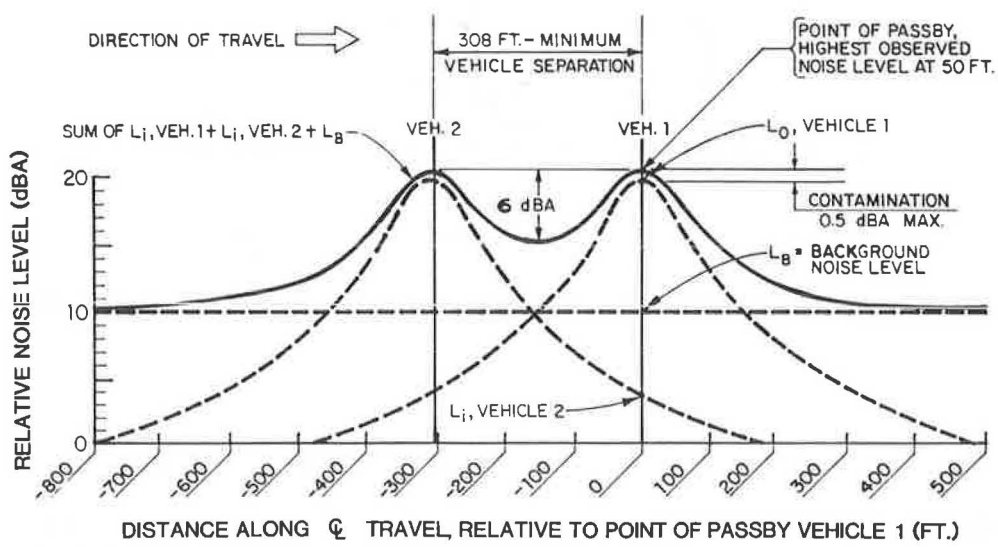
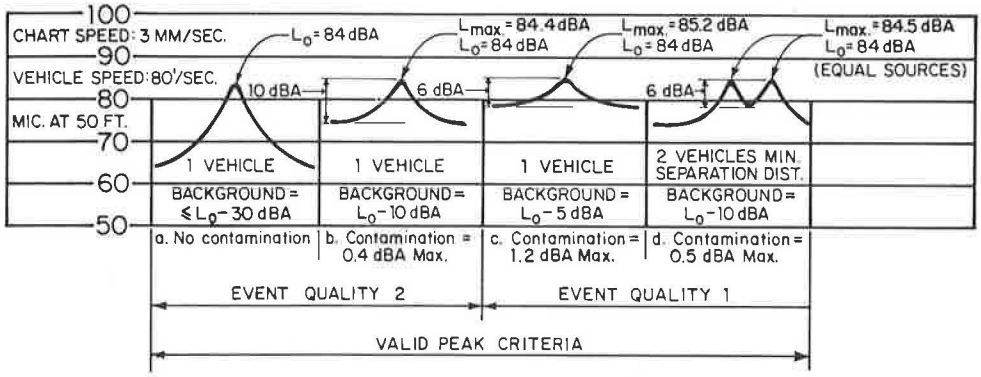


FIGURE 4 Minimum separation between two heavy trucks.



NOTES:
- L_0 = Vehicle Noise Emission Level.
- $L_{max.}$ = Highest Observed Noise Level.
- Contamination = $L_{max.}$ − L_0
- When $L_{max.}$ − Background Level <6 dBA, Event Was Rejected. (Event Quality 0)

FIGURE 5 Valid peak and event criteria.

ence microphones were categorized into three event-quality groups:

Quality 0: peak less than 6 dBA rise and fall,
Quality 1: peak 6 to 9 dBA rise and fall, and
Quality 2: peak 10 dBA or more rise and fall.

All quality 0 peaks were rejected. Quality 1 and 2 peaks were accepted. Of a total of 1,905 heavy-truck measurements at Microphone 2 (reference microphone), the following statistics were derived:

Quality 0: 136, or 7.1 percent (rejected);
Quality 1: 295, or 15.5 percent (accepted); and
Quality 2: 1,474, or 77.4 percent (accepted).

Of the previous 1,769 accepted measurements, 83.3 percent were of quality 2 and 16.7 percent of quality 1.

In addition to the valid peak and vehicle-separation criteria, the observers also used subjective judgments to evaluate whether a measurement was contaminated. For instance, both observers were on their guard against contamination from background or other traffic noise that rose and fell with the target peak.

SAMPLE SIZE

Preliminary data, analyzed from the +3.0 and +6.0 percent sites, showed a range of truck speeds from 10 to 57 mph. Regression analyses indicated that the slope of the line of best fit through plots of noise levels versus log speed was shallow enough to allow grouping of noise levels in speed classes of 10 mph at both sites without deviation of the center points of the speed classes more than 1 dBA from the edges. On the basis of this preliminary information, the following speed classes were designed to cover the entire range of expected speeds: <11, 11 to 20, 21 to 30, 31 to 40, 41 to 50, 51 to 60, and >60 mph.

After all the data had been gathered, the minimum sample size required for the mean of each speed class at each site to be determined within ± 1 dBA (95 percent confidence level) was calculated by

$$n_{min} = \left[(t_{\alpha/2;n-1})(s)/d \right]^2 \qquad (1)$$

where

$t_{\alpha/2;n-1}$ = amount of sample standard deviations associated with $(1 - \alpha) \times 100$ percent confidence level and $n - 1$ degrees of freedom,
s = sample standard deviation,
α = level of significance (=.05),
d = $(1 - \alpha) \times 100$ percent confidence interval around the mean (±1 dBA),
n_{min} = minimum required number of samples, and
n = number of samples gathered.

Table 1 shows the number of events measured and the minimum required for all sites combined. Table 2 shows the energy means, means, standard deviations, number of observations, minimum required, and mean speed for each of the six sites by speed class. The data were measured at the 50-ft reference microphone.

TABLE 1 Number of Events Sampled and Minimum Required by Vehicle Group and Speed Class

Speed Class	Speed Range (mph)	Events Sampled	Minimum Required
0	<11	2	—[a]
1	11–20	143	30
2	21–30	539	25
3	31–40	503	27
4	41–50	325	22
5	51–60	229	19
6	>60	28	17

Note: Data are for heavy trucks on grades of +3 to 7 percent; minimums are those required for 95 percent confidence interval of ±1 dBA around mean of speed class.
[a]Unable to determine accurately.

ANALYSES AND RESULTS

Examination of measured truck noise levels at 50 ft revealed 29 data points (1.7 percent of total) to be more than 90 dBA, which is the legal limit for any vehicle under any operating condition in California.

The 1.7 percent violations occurred in all speed classes when the data of all sites were pooled but

TABLE 2 Data Summary of 50-ft Reference Microphone

Speed Class (mph)	Type of Data	Grade (%) +3.0	+4.2	+4.5	+5.6	+6.0	+7.0
11-20	Energy mean (dBA)	–	85.4	83.6	82.0	83.4	83.8
	Mean (dBA)	–	84.0	82.8	81.0	83.4	83.2
	Standard deviation	–	4.8	3.1	2.9	2.7	2.2
	No. of observations	–	4	13	15	65	45
	Minimum required[a]	–	[b]	46	38	30	19
	Mean speed (mph)	–	18.3	17.7	17.9	17.5	17.6
21-30	Energy mean (dBA)	85.5	82.8	81.5	82.1	82.5	83.0
	Mean (dBA)	83.8	81.8	80.8	81.4	81.9	82.4
	Standard deviation	4.0	2.7	2.4	2.5	2.3	2.2
	No. of observations	10	41	109	139	145	83
	Minimum required[a]	81	29	24	25	21	19
	Mean speed (mph)	27.5	28.0	26.7	26.0	24.5	24.7
31-40	Energy mean (dBA)	83.9	83.2	82.5	82.6	81.8	83.6
	Mean (dBA)	83.2	82.6	81.4	81.8	81.2	82.9
	Standard deviation	2.4	2.3	2.8	2.6	2.3	2.4
	No. of observations	83	92	118	58	51	98
	Minimum required[a]	24	20	31	27	21	24
	Mean speed (mph)	36.3	34.7	34.0	33.3	35.8	35.3
41-50	Energy mean (dBA)	83.1	84.5	83.0	84.3	82.4	84.1
	Mean (dBA)	82.4	83.9	82.4	83.6	82.0	83.7
	Standard deviation	2.4	2.3	2.2	2.4	1.9	2.1
	No. of observations	105	42	35	41	23	73
	Minimum required[a]	22	21	18	23	15	17
	Mean speed (mph)	45.2	44.5	45.1	44.7	45.7	44.8
51-60	Energy mean (dBA)	84.0	85.7	84.1	85.4	83.4	85.3
	Mean (dBA)	83.4	85.1	83.6	84.9	83.1	84.4
	Standard deviation	2.2	2.2	1.9	1.9	1.5	3.1
	No. of observations	111	27	35	34	11	6
	Minimum required[a]	19	21	15	15	12	63
	Mean speed (mph)	55.6	54.3	55.2	53.9	55.2	52.5
>60	Energy mean (dBA)	84.5	–	85.2	88.6	–	–
	Mean (dBA)	84.1	–	85.0	88.3	–	–
	Standard deviation	1.8	–	1.5	2.5	–	–
	No. of observations	23	–	3	2	–	–
	Minimum required[a]	13	–	[b]	[b]	–	–
	Mean speed (mph)	62.5	–	61.7	62.0	–	–

Note: Dash indicates no data in this speed class.
[a]Minimum required for 95 percent confidence level of ±1 dBA around mean.
[b]Not enough data to determine accurately.

not when each site was considered separately. This presented problems in that the sporadic high values created anomalies in speed and grade analyses.

For the purpose of developing grade noise emission curves, the 29 values over 90 dBA were omitted from the data. The data summary in Table 2 does not include these values. After the curves had been developed, the values were again included and distributed proportionally over all speed classes.

The 1,740 values of 90 dBA and less were examined for grade and speed dependencies. At the outset of this study, both dependencies were anticipated. The final products of the grade noise research were envisioned to be a family of speed-dependent curves for grades up to 7 percent in increments of 1 percent.

Two potential problems needed to be addressed before the grade and speed dependency analyses were begun: possible variations in site characteristics and possible differences in source characteristics, such as truck populations and pavement type and condition.

In the level-road noise emission study, data from 16 sites were used to analyze basically one condition: level roads. This relatively large number of sites allowed fairly detailed analyses of variations in site characteristics and vehicle populations. The final emission levels represented the average of a large variety of conditions.

For the analyses of noise levels on grades, however, each condition (percentage of grade) was represented by only one site. Ideally, several sites should have been selected for each percentage of grade. This, however, would have greatly increased the scope and total costs of the project.

Variability in Site Characteristics

At four of the six grade sites, the three-microphone setup was used (Figure 2). This allowed comparisons to be made of Microphone 1 to Microphone 2 and Microphone 1 to Microphone 3 noise drop-offs between the four sites. This information was used to determine whether ground characteristics were acoustically similar from site to site (+3.0 percent, +4.5 percent, +6.0 percent, +7.0 percent). Ground characteristics at the two remaining sites employing one microphone each could obviously not be verified in this manner. They appeared very similar, however, and there were no reasons to suspect that noise drop-offs would be significantly different at these sites (+4.2 and +5.6 percent).

The noise drop-offs are shown in Table 3. Comparison with the drop-offs for hard and soft sites in the level-road study revealed that the grade sites were somewhere in between, as had been expected. As was noted in the level-road study, the noise drop-offs do not appear to be speed dependent.

To see whether there were statistically significant differences in ground characteristics, the measured data at the 50-ft microphones were normalized via the 25-ft microphones. This method assumed that, because of the proximity of the source, the 25-ft microphones were not affected by ground characteristics. Any differences between sites at that distance could then be attributed to differences in source characteristics, such as truck populations and pavement. By setting all the 25-ft microphone (Microphone 1) values equal and correcting the 50-ft microphone (Microphone 2) values appropriately, proper comparisons could be made of site characteristics.

TABLE 3 Average Noise Drop-Offs on Grade Sites

	Microphone 1 to Microphone 2 (dBA) by Grade					Microphone 1 to Microphone 3 (dBA) by Grade				
Speed Class (mph)	+3.0 Percent	+4.5 Percent	+6.0 Percent	+7.0 Percent	All	+3.0 Percent	+4.5 Percent	+6.0 Percent	+7.0 Percent	All
11-20	–	–	5.8	6.5		–	–	5.3	6.2	
21-30	–	6.8	6.1	6.1		–	6.1	5.7	5.7	
31-40	6.3	6.0	6.0	6.1		5.7	5.6	5.5	5.5	
41-50	6.5	6.3	5.9	5.9		6.0	5.5	5.4	5.5	
51-60	6.3	6.4	6.0	–		5.9	5.7	5.5	–	
>60	6.5	–	–	–		5.9	–	–	–	
All speeds	6.4	6.3	6.0	6.1		5.9	5.8	5.5	5.7	
All sites					6.2					5.8

Note: Dash indicates not enough data in speed class.

A one-way analysis of variance (ANOVA) was then performed on the normalized 50-ft data for three cases: all speed classes, 31 to 40 mph, and 41 to 50 mph. The latter two speed classes were the only ones with enough data (95 percent confidence interval of mean ± 1 dBA) at all four sites. Table 4 shows the results. In all cases, no significant differences could be detected at a significance level of .05. The sites appeared, therefore, to have the same ground characteristics. The supporting statistics for Table 4 are as follows (α = .05):

TABLE 4 Analysis of Variance: Site Characteristics

	Grade (%)			
Normalized 50-ft Data	+3.0	+4.5	+6.0	+7.0
All Speed Classes[a]				
Energy mean (dBA)	81.6	81.6	82.0	81.9
Standard deviation	2.08	2.67	2.38	2.29
No. of observations	332	313	295	305
31 to 40 Mph[a]				
Energy mean (dBA)	81.4	81.8	81.8	81.7
Standard deviation	2.43	2.77	2.31	2.43
No. of observations	83	118	51	98
41 to 50 Mph[a]				
Energy mean (dBA)	81.9	82.0	82.4	82.4
Standard deviation	2.35	2.15	1.89	2.06
No. of observations	105	35	23	73

[a]Conclusion: There are no significant differences in site characteristics.

Speed Class (mph)	F-Ratio	Critical F
All	2.35	2.60
31-40	0.47	2.60
41-50	0.91	2.60

Variability in Source Characteristics

Source characteristics are composed of several elements, such as truck characteristics (engine noise, stack noise, tire noise, etc.), pavement characteristics (new, old, asphalt concrete, portland cement concrete, grooved, smooth, etc.), truck speed, and road gradient. The latter two were the variables to be examined to the extent that they affected the uphill heavy-truck noise (speed and grade dependency).

Speed dependency for a given grade may easily be examined because the analysis is made entirely within the same source population distribution. Analysis of grade dependency, however, is complicated by the necessity of comparing potentially different source populations, as shown in Figure 6.

It is virtually impossible to quantify the acoustical effects of individual elements in each source population and to separate them from the total noise measurements. At best, the effects caused by site and speed variations may be removed from the measurements by examining noise levels at the 25-ft microphone locations only within each speed class. In addition to the sought-after effects of grades, however, two other variables still remain: truck populations and pavement.

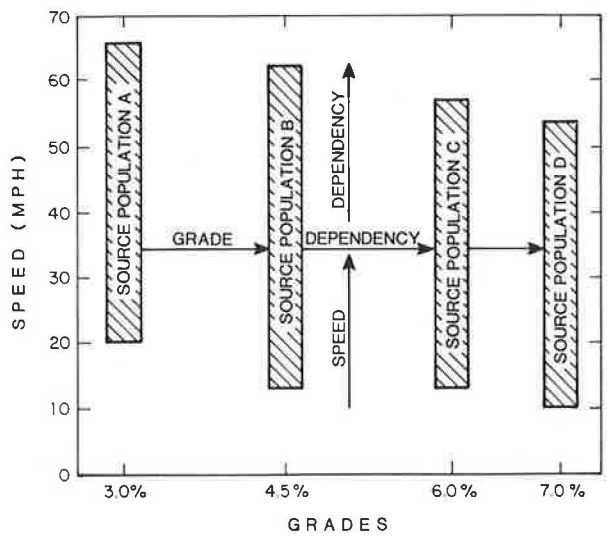


FIGURE 6 Speed dependency versus grade dependency.

Tables 5 and 6 show that there were significant differences between source characteristics at 31 to 40 mph and at 41 to 50 mph when data from the four sites were subjected to the ANOVA test. Further examination revealed that at 31 to 40 mph, the +3.0 and +7.0 percent sources were not significantly different. Similarly, the +4.5 and +6.0 percent sources appeared to be the same in the 31 to 40 mph speed range. In the 41 to 50 mph speed class, the +3.0, +4.5, and +7.0 percent sources appeared to be the same, whereas the +6.0 percent source population appeared different from the rest.

Because of the tendency of the data to be paired at the extremes (+3.0 and +7.0 percent) and in the middle (+4.5 and +6.0 percent), the differences between source characteristics could not be explained by a simple direct grade dependency. The supporting

TABLE 5 Analysis of Variance: Source Characteristics, 31-40 Mph Speed Class

	Analysis 1[a] by Grade (%)				Analysis 2[b] by Grade (%)			Analysis 3[c] by Grade (%)		Analysis 4[d] by Grade (%)	
25-ft Data	+3.0	+4.5	+6.0	+7.0	+3.0	+4.5	+7.0	+3.0	+7.0	+4.5	+6.0
Energy mean (dBA)	90.3	88.5	87.8	89.7	90.3	88.5	89.7	90.3	89.7	88.5	87.8
Standard deviation	2.28	2.47	2.24	2.38	2.28	2.47	2.38	2.28	2.38	2.47	2.24
No. of observations	82	115	49	95	82	115	95	82	95	115	49

[a]Conclusion: Sources are different.
[b]Conclusion: Sources are different.
[c]Conclusion: There is no difference in source characteristics.
[d]Conclusion: There is no difference in source characteristics.

TABLE 6 Analysis of Variance: Source Characteristics, 41-50 Mph Speed Class

	Analysis 1[a] by Grade (%)				Analysis 2[b] by Grade (%)		
25-ft Data	+3.0	+4.5	+6.0	+7.0	+3.0	+4.5	+7.0
Energy mean (dBA)	89.5	89.3	88.3	90.0	89.5	89.3	90.0
Standard deviation	2.34	2.09	1.94	1.94	2.34	2.09	1.94
No. of observations	105	33	23	70	105	33	70

[a]Conclusion: Sources are different.
[b]Conclusion: There is no difference in source characteristics.

statistics for Tables 5 and 6 are as follows (α = .05):

Speed Class	F-Ratio	Critical F
31-40 mph		
Analysis 1	16.36	2.60
Analysis 2	14.72	2.99
Analysis 3	2.92	3.90
Analysis 4	2.92	3.91
41-50 mph		
Analysis 1	3.74	2.60
Analysis 2	1.56	3.04

Grade Dependency

The suspicion that no grade dependency could be detected was confirmed when the energy means of the 25-ft microphones were plotted by speed class versus percentage grade in Figure 7. This is not to say that there was no grade dependency. However, the variations, possibly due to truck population differences, pavement type or condition, or both, were large enough to mask any grade dependency.

A hypothetical case shown in Figure 8 presents an explanation for the lack of strong, direct grade dependency. Both trucks in the figure are assumed to be identical in all pertinent aspects with the exception of gross vehicle weight. For both vehicles to maintain equal crawl speeds, the truck on the steeper grade must carry a lighter load than the truck on the shallow grade. The expected noise increase due to the steeper grade would to some degree be offset by the expected decrease in noise due to the lighter load. Under this hypothesis, the noise emission levels of both trucks would approach equality if their crawl speeds were also equal, regardless of grade. Further research, taking into account gross vehicle weight and power, is strongly recommended to test the hypothesis.

Additional plots of noise levels at 50 ft versus grades (Figure 9) further support the foregoing hypothesis. Variations, possibly due to differences in truck populations and pavement conditions, were probably greater than any variation caused by grades.

Speed Dependency

Because of a lack of observed grade dependency, the data from all sites could be pooled for the analyses of emission level versus speed. This had the obvious advantage of allowing the averaging of variations in truck populations and pavements at all six sites.

Before the data were pooled, speed-dependent curves of noise emission levels at 50 ft at each site were plotted by energy means versus average speed of each speed class (Figure 10). These plots suggest that at each site, a curve of best fit would tend to be best described by a second-degree polynomial equation of the general form:

$$y = a + bx + cx^2 \quad (2)$$

rather than a linear regression equation. In the foregoing expression, $y = 10^{L_O/10}$ = the relative energy of the heavy-truck noise level, $x = \text{Log}_{10}$ (speed, mph), and a, b, and c are mathematically determined coefficients.

Substituting y and x in Equation 2, the equation becomes

$$10^{L_O/10} = a + b[\text{Log}_{10}(\text{speed})] + c[\text{Log}_{10}(\text{speed})]^2 \quad (3)$$

and, converting relative energy to energy mean noise level,

$$L_{\overline{OE}} = 10\text{Log}_{10}\{a + b[\text{Log}_{10}(\text{speed})] + c[\text{Log}_{10}(\text{speed})]^2\} \quad (4)$$

Figure 11 shows second-order polynomial plots for each site. Both Figures 10 and 11 appear to support the earlier finding of lack of direct grade dependency.

Figure 12 shows a comparison of $L_{\overline{OE}}$ versus Log_{10} • (speed) plots. They were generated from 1,740 data points from all six sites at 50 ft (excluding the 29 data points above 90 dBA). Three methods were used to generate the curves. They were named after the programs used to develop their equations:

1. Linear regression (Linreg),
2. Plotting energy means of the six speed classes (Veno), and
3. Second-order polynomial curve fit (Polfit).

The comparisons clearly indicate that Veno and Polfit were in close agreement. Of these two methods, Polfit

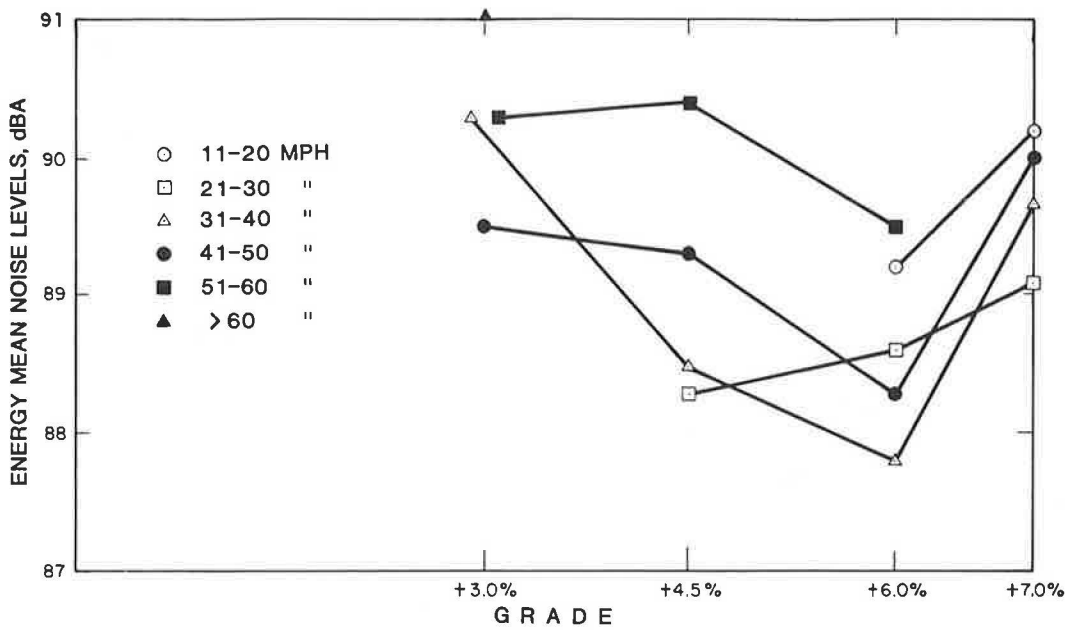


FIGURE 7 Energy mean noise levels at 25 ft versus grade by speed class.

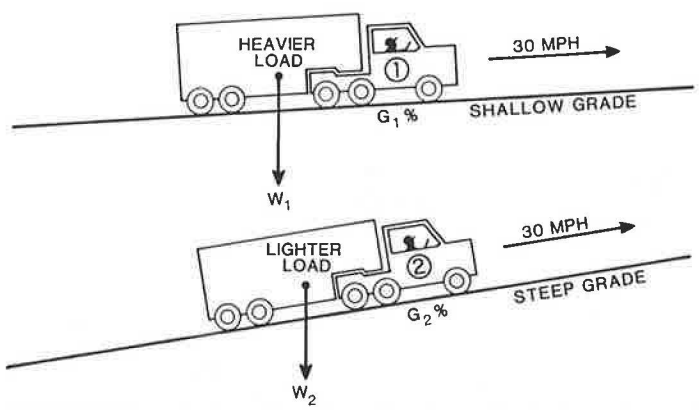


FIGURE 8 Sustained crawl speed as a function of load and percentage of grade ($G_1 W_1 \cong G_2 W_2$).

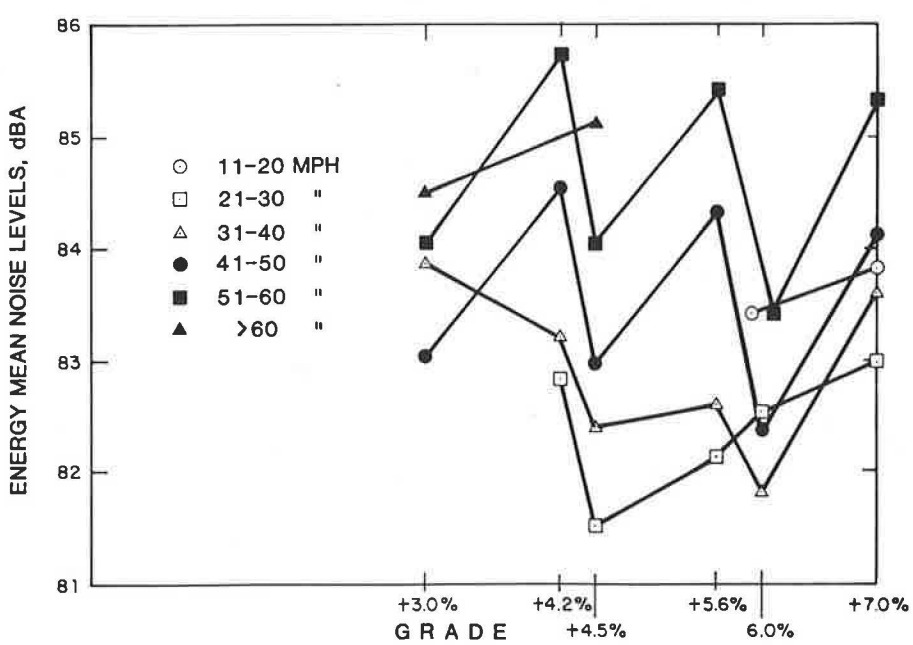


FIGURE 9 Energy mean noise levels at 50 ft versus grade by speed class.

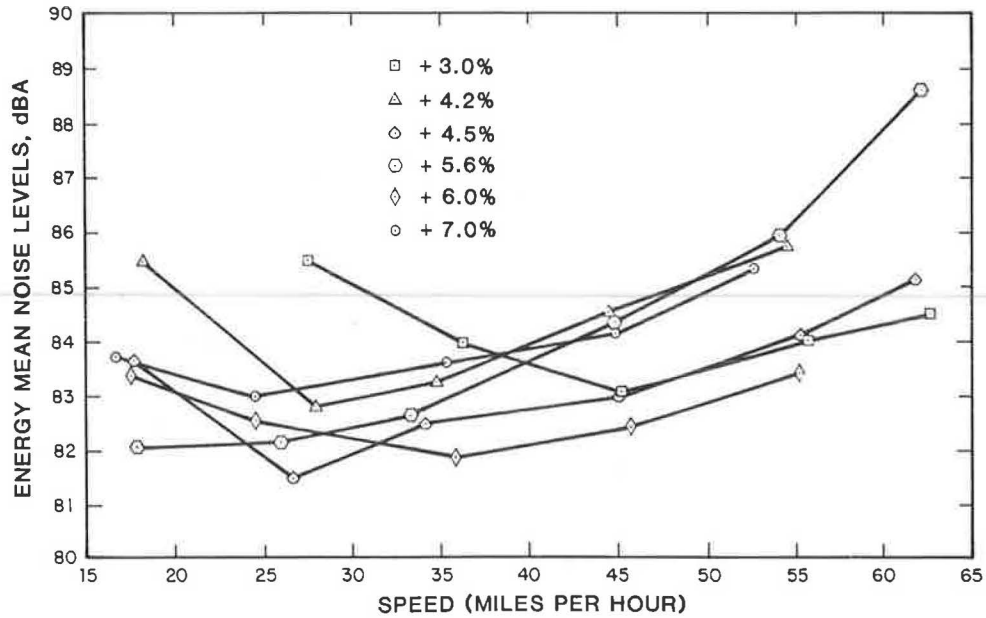


FIGURE 10 Plots by means of 10-mph speed classes (speed versus L_{eq}).

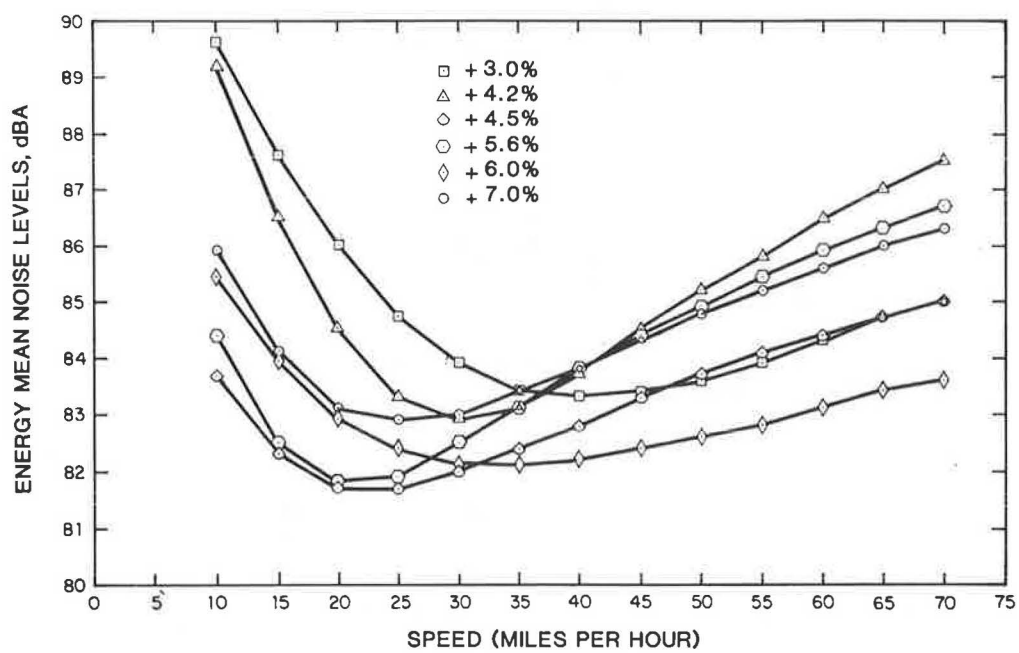


FIGURE 11 Energy averaged second-degree polynomial plots (individual sites, 50-ft data).

represents a better fit through all the data, whereas the Veno curve only represents the means of the 10-mph speed class. Polfit was therefore selected to represent a speed-dependent energy mean emission curve for heavy trucks going uphill on grades ranging from +3 to +7 percent using data of 90 dBA or less at 50 ft. The equation of this curve is

$$L_{\overline{OE}} = 10\mathrm{Log}_{10}\{2.0295 \times 10^9 - 2.6266 \times 10^9[\mathrm{Log}_{10}(\mathrm{speed})] + 9.3158 \times 10^8[\mathrm{Log}_{10}(\mathrm{speed})]^2\} \quad (5)$$

The units for $L_{\overline{OE}}$ are in adjusted decibels, those for speed, in miles per hour.

The 29 data points above 90 dBA, omitted in the development of the Polfit curve, were used to adjust the curve upward to include the 1.7 percent violators. The adjustment constant was calculated from the energy mean noise level of all the 50-ft data (including those over 90 dBA) and the energy mean noise level of the ≤90-dBA data. The difference between these was 0.8 dBA, which was used as a constant to adjust the curve upward equally at all points. This assumes that the distributions of <90 dBA and >90 dBA are proportional over all speed

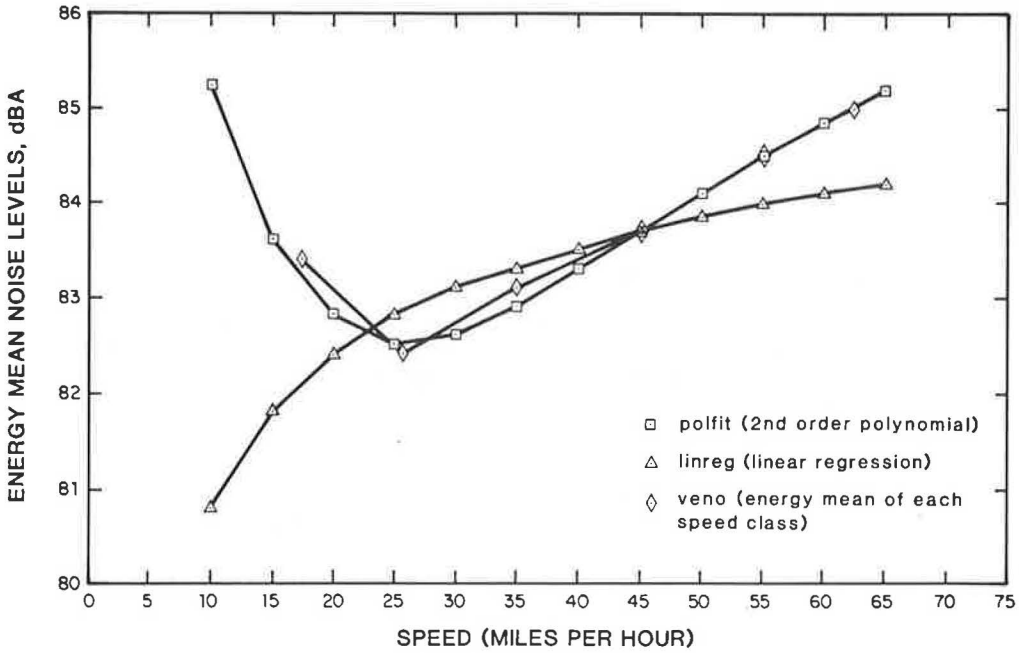


FIGURE 12 $L_{\overline{OE}}$ versus log speed, three methods (all sites combined, 50-ft data).

classes. When the data of all sites were pooled, the assumption proved to be valid in almost all speed classes.

The adjusted curve's equation is

$$L_{\overline{OE}} = 10\mathrm{Log}_{10}\{2.0295 \times 10^9 - 2.6266 \times 10^9[\mathrm{Log}_{10}(\mathrm{speed})] + 9.3158 \times 10^8[\mathrm{Log}_{10}(\mathrm{speed})]^2\} + 0.8 \quad (6)$$

which represents the California heavy-truck-on-grade (Calgrade) noise reference energy mean emission levels for sustained speeds on grades of +3 to +7 percent. This curve is shown in Figure 13.

Speed Distribution as a Function of Grades

Earlier it was concluded that there was a lack of direct grade dependency in the measured noise data. However, there was a significant speed dependency, represented by the Calgrade curve. Examination of observed speed distributions in this study show that, as expected, speeds and grades are inversely proportional. Unlike level-road sites, where free-flowing traffic moves within a narrow range of speeds, grades display a much wider range. Using average speeds with Calgrade may present problems, depending on the speed distributions used. Average speeds generally tend to be near the sag point of the curve. Ob-

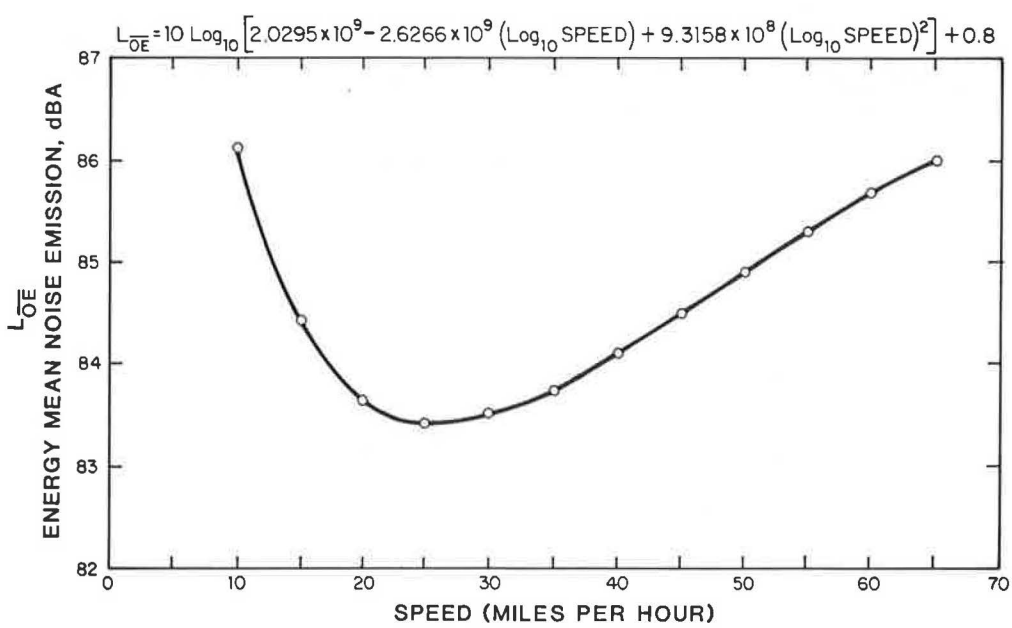


FIGURE 13 California heavy truck-on-grade noise reference energy mean emission levels, grades +3 to +7 percent.

viously, when speed distributions are sharply divided between extremely high and low speeds, integration of the entire speed distribution over Calgrade may give much higher but more accurate results. Speed distributions, however, are not readily available on a routine basis for traffic noise studies. For that reason, "default" emission levels were developed for each grade based on speed distributions observed in this study. For these to be useful, the observed speed distributions on the six grades would have to be "typical."

Figure 14 shows frequency distributions of speeds observed at each site. A previously published Caltrans study (6) reported the average and 12.5-percentile truck speeds in California for each grade from 0 to +7 percent. The observed values were compared with these, and they are shown in Table 7. The average and 12.5 percentile of the observed distributions generally showed good agreement with those of the typical California distributions. It was therefore concluded that the observed distributions were fairly typical and useful for default emission levels.

The weighted $L_{\overline{OE}}$ for each grade's speed distribution was calculated, and plots were made. A curve of best fit was then drawn through the plots (Figure 15) and suggested default values were selected from this curve for whole increments of 1 percent, as follows:

Grade (%)	$L_{\overline{OE}}$ (dBA)
3	84.7
4	84.1
5	83.9
6	83.9
7	83.9

The suggested values should only be used for heavy trucks traveling uphill [as defined in Report FHWA RD-77-108 (3)] at sustained crawl speeds on grades ranging from 3 to 7 percent.

In absence of 1 and 2 percent grades in these analyses, interpolation between the Calveno heavy-truck emission level for 55 mph on level roads (83.8 dBA) and the 3 percent default value for grades between 0 and 3 percent is suggested.

Finally, comparisons were made between using average speeds and entire speed distributions (Table 8) and the Calgrade versus the NCHRP Report 117 grade-correction method recommended in Report FHWA

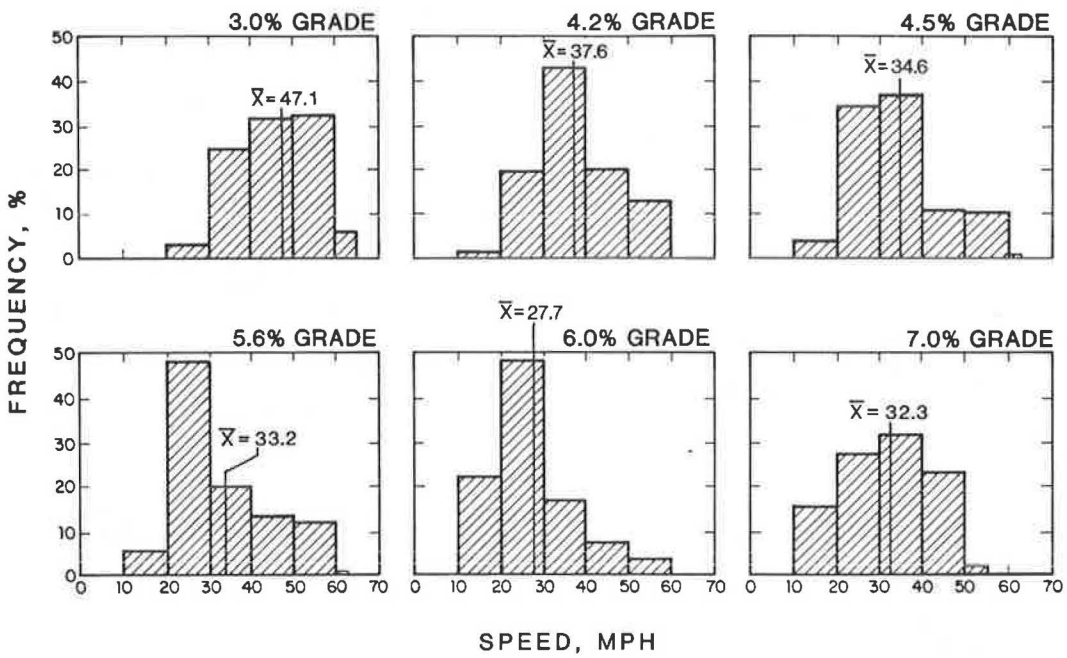


FIGURE 14 Speed distributions by grade.

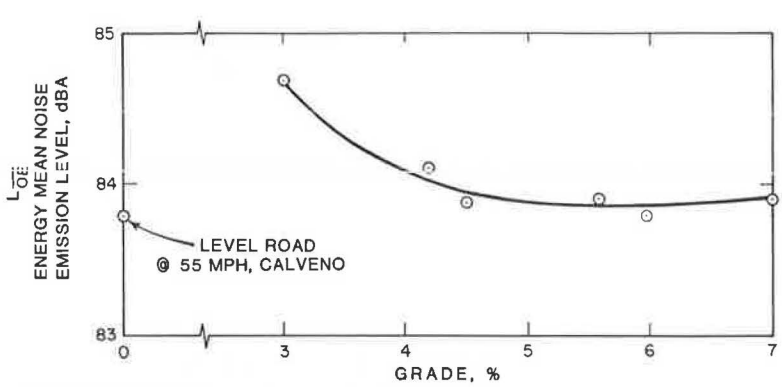


FIGURE 15 Weighted noise emission levels for observed speed distributions, heavy trucks uphill on +3 to +7 percent grades.

TABLE 7 Observed Versus Typical Speeds

Grade (%)	Average Truck Speed (mph)		12.5 Percentile Truck Speed (mph)	
	Observed	Typical[a]	Observed	Typical[a]
+3.0	47.1	44.7	35	33.5
+4.2	37.6	39.2	29	25.9
+4.5	34.6	38.0	25	24.5
+5.6	33.2	33.9	23	20.3
+6.0	27.7	32.5	18	19.1
+7.0	32.3	30.7	19	17.0

[a]F. D. Rooney, Speeds of Trucks and Other Vehicles on Grades *(6)*.

TABLE 8 $L_{\overline{OE}}$ Based on Average Speed Versus $L_{\overline{OE}}$ Based on Entire Speed Distribution

Grade (%)	Avg Observed Speed (mph)	Calgrade $L_{\overline{OE}}$ (dBA)	
		Based on Avg Speed	Based on Entire Speed Distribution
+3.0	47.1	84.7	84.7
+4.2	37.6	83.9	84.1
+4.5	34.6	83.7	83.9
+5.6	33.2	83.6	83.9
+6.0	27.7	83.4	83.8
+7.0	32.3	83.5	83.9

TABLE 9 $L_{\overline{OE}}$ Based on Calgrade and NCHRP Report 117 Methods

Grade (%)	Avg Typical Speed (mph)	$L_{\overline{OE}}$ (dBA) Based on Avg Speed	
		Calgrade	NCHRP Report 117
+3	45	84.5	83.1
+4	40	84.1	83.2
+5	36	83.8	83.3
+6	32.5	83.5	84.3
+7	31	83.4	85.5
Level (0-2)	55	83.8	83.8

RD-77-108 (3) (Table 9). The latter shows differences of up to 2.1 dBA between the two methods.

ACKNOWLEDGMENTS

This study was performed in cooperation with FHWA. A copy of the detailed report, titled California Vehicle Noise Emission Levels (Final Report), by the same author, will be available from Caltrans sometime in 1986.

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