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Air-Quality and Noise Issues in Environmental Planning

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Traffic Flow and Air Quality in a Mountain Community

PAUL E. BENSON, WILLIAM A. NOKES, and ROBERT L. CRAMER

ABSTRACT

The air-quality impacts of a comprehensive transportation improvement project located in the ski resort community of Mammoth Lakes, California, are analyzed by comparing levels of carbon monoxide sampled before and after construction. The project incorporates widening, channelization, installation of fully actuated signals, and construction of bus stop shelters. The elements of a transportation control plan designed to mitigate potential air-quality impacts of the project are described and their effectiveness is assessed.

Mammoth Lakes, located in the Eastern Sierra Region at an elevation of 8,200 ft, is an area of burgeoning growth centered around the largest single ski resort operation in California. By 1980 a combination of traffic congestion, wood-burning stoves, and winter meteorology had caused a significant decline in the region's air quality. Traffic congestion along State Route 203, particularly at the Lake Mary Road intersection, was a major contributor to this problem. Route 203 provided the only access to the main ski-lift facilities and therefore experienced heavy congestion on holiday weekends during the ski season.

To reduce congestion and improve traffic safety on Route 203, a transportation improvement project was constructed in 1981-1982. The route was widened to four lanes, delineation was improved, and several intersections, including Lake Mary Road, were upgraded with fully actuated traffic signals. Bus stop shelters were constructed in an effort to promote the use of an existing bus service and further reduce traffic congestion within the corridor. The improvements were expected to double the capacity of the route and reduce carbon monoxide (CO) emissions by improving traffic flow. However, CO emissions would drop only if the added capacity did not induce substantial increases in traffic volume.

During the planning phase of the project, a transportation control plan was developed to mitigate any adverse air-quality impacts brought on by the increased capacity of the route (1). The plan contained strategies designed to increase use of public transit, improve traffic flow, and control traffic volumes. The major components of the plan included parking restrictions, construction of transit amenities, and an expansion of the county road system to help relieve congestion on Route 203. Operational improvements such as staggered ski-lift closing times, a "ski-back" trail, and lighting of ski runs for night skiing were also included. Future expansion of ski facilities would only be permitted if peak traffic volumes on Route 203 did not increase. Transit service was to be required for any new facilities, but no expansion of parking capacity would be allowed.

To check the adequacy of the mitigation measures, the plan included a provision for pre- and postconstruction CO monitoring. The preconstruction aerometric survey was conducted as a joint effort between California Department of Transportation (Caltrans) District 9 and the Transportation Laboratory during the winter of 1980-1981. A postconstruction survey was conducted during the winter of 1982-1983. In this paper the results of this before-and-after study are discussed and the effectiveness of the transportation improvements at mitigating air-quality problems associated with traffic congestion is evaluated.

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CARBON MONOXIDE MONITORING PROGRAM

The junction of Route 203 and Lake Mary Road shown in Figure 1 carries traffic on three primary legs. The fourth (southerly) leg, planned for extension and widening by others, now carries less than 1 percent of the traffic handled by the intersection. During the 1980-1981 ski season, the intersection was controlled by a pretimed, two-phase signal with lights mounted at the corners. Roadway width limitations permitted only two approach lanes per leg with

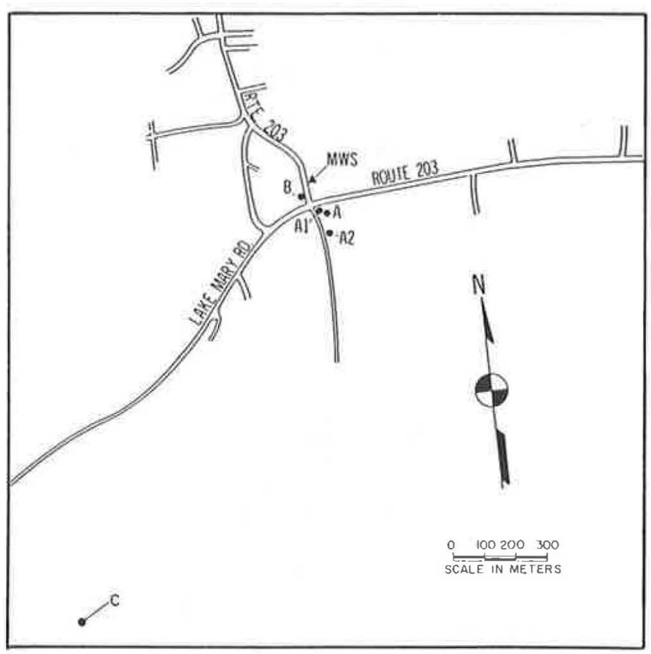

FIGURE 1 Sampling locations for the 1980-1981 and 1982-1983 air-quality monitoring programs at Mammoth Lakes, California.

no room for channelization. Widening of the route made room for three approach lanes on eastbound Route 203 and Lake Mary Road and four lanes on westbound Route 203. A fully actuated three-phase signal was also installed.

CO concentrations were sampled at five sites shown in Figure 1 during the pre- and postconstruction surveys. Four of the sampling sites were clustered around the Route 203-Lake Mary Road intersection. The fifth site, located approximately 1 km southwest of the intersection, provided a measure of ambient CO concentration for the area. A mechanical weather station located at the intersection recorded wind direction, wind speed, and temperature at a height of 10 m. A larger meteorological tower located about 1.5 km east of the intersection measured wind speed and temperature at heights of 10 and 18 m.

Air samples were collected over 1-hr intervals using continuous-flow bag samplers. The bags were returned to the District 9 Laboratory and tested for CO within 48 hr of collection by using nondispersive infrared analysis. Days that were favorable for skiing, particularly weekends and holidays, were monitored. In the 1980-1981 season, samples were collected on 63 days from December through February. For the 1982-1983 season, 45 days were sampled from November through February. Although some 24-hr sampling was done, most was conducted between the hours of 7:00 a.m. and 7:00 p.m.

Traffic counts were made at the intersection by District 9 personnel during the peak ski weekends for each season. For the 1980-1981 season, counts were made in February on the weekend following Lincoln's Birthday. For the 1982-1983 season, counts were made in December on the weekend before New Year's Day. The counts recorded 15-min volumes by direction and vehicle type from 7:00 a.m. to 7:00 p.m.

DATA ANALYSIS AND DISCUSSION

The hourly CO concentrations recorded for each day were stratified into three measures of air-quality impact: the daily 8-hr maximum, the 1-hr morning maximum, and the 1-hr evening maximum. Morning and evening maximums were taken from days with valid measurements at Sites A and B for the hours of 7:00 to 10:00 a.m. and 4:00 to 7:00 p.m., respectively. Daily 8-hr maximums were recorded when no more than 2 consecutive hr or 3 hr total were missing for Sites A and B from 7:00 a.m. to 7:00 p.m. Missing values on days satisfying these criteria were approximated by linear interpolation (2). The resulting number of days analyzed by season and averaging time are as follows:

Averaging	No. of Days	
Time (hr)	1980-1981	1982-1983
1 (a.m.)	35	37
1 (p.m.)	33	40
8	31	38

The two ski seasons involved in this analysis were far from similar in nature. The 1980-1981 season started much later than normal, with most of the peak ski days occurring during February and March of 1981. By contrast, the 1982-1983 season was much longer, with capacity crowds arriving by Thanksgiving of 1982 and operations tapering off in the spring of 1983. In order to compare air-quality measurements for the two seasons, factors independent of the transportation improvements that might have an impact on air quality had to be considered. These factors were meteorology, demand volume, and vehicle emissions.

Meteorology was the first factor to be considered. An attempt to normalize the data by using wind speed, temperature, and stability measurements was made. However, significant gaps in the meteorological data base and excessive scatter in the normalized results forced this approach to be abandoned. Instead, average hourly wind speeds measured at the intersection from 7:00 to 10:00 a.m. and 4:00 to 7:00 p.m. were examined to see whether there was a significant difference between the two seasons. Based on over 200 hr of available data, no significant difference was found between the seasonal means for either morning or evening conditions. Furthermore, similar low-wind-speed weather conditions favorable for skiing were expected to correlate with peak traffic volumes and CO concentrations regardless of which season was considered. Therefore, the overall effects of meteorology on corridor CO concentrations were assumed to be approximately equal for the two seasons.

The second factor to be accounted for was demand volume. Because traffic counts were not available for most of the days sampled, a surrogate measure was needed to quantify this factor. Daily sales of ski-lift tickets reported to the Forest Service, U.S. Department of Agriculture (USDA), by the ski operator were used for this purpose. Because Route 203 was the only road that served the main ski-lift facility, ticket sales offered the most direct measure of demand volume available. The distribution of number of days analyzed by ticket sales category for each daily maximum is given in Figure 2 for both the 1980-1981 and 1982-1983 seasons. All three distributions show a substantially greater number of days with high ticket sales sampled in the 1982-1983 season. Average daily ticket sales were 97 percent higher than those in the 1980-1981 season. Ticket sales on peak ski days were similar for both seasons, but there were many more peak days in the 1982-1983 season.

The final factor to be considered was the change in composite vehicle emissions between seasons. The 1982-1983 vehicle fleet contained a higher percentage of new vehicles with better emission controls than the 1980-1981 fleet. Composite CO emissions for the two seasons were estimated by using a California emission factor program (3). An average decrease from 1980-1981 emissions of 10 percent was forecast.

Of the three factors considered, the change in average demand volume between the two seasons was the most important. It was expected that higher ticket sales would result in more congestion and therefore higher CO concentrations at the intersection. To test this idea, 8-hr daily maximum CO concentrations were plotted against ticket sales for the intersection sites and ambient site. Regression lines and 95 percent confidence limits were constructed for each season (see Figure 3). As expected, CO concentrations at the intersection sites generally increased as ticket sales increased. A similar but weaker trend was apparent for the ambient site.

The two regression lines in Figure 3b indicate that the transportation improvements led to an average reduction in 8-hr CO concentrations near the intersection of about 50 percent for days with low to medium ticket sales. For days with high ticket sales (>10,000), the average reduction ranged from 13 to 25 percent, or about the amount expected from improved control technology alone. This suggests that the improvements to the intersection had a measurable positive effect on nearby air quality for low to medium traffic volumes but were not effective at improving air quality as volumes approached the ca-

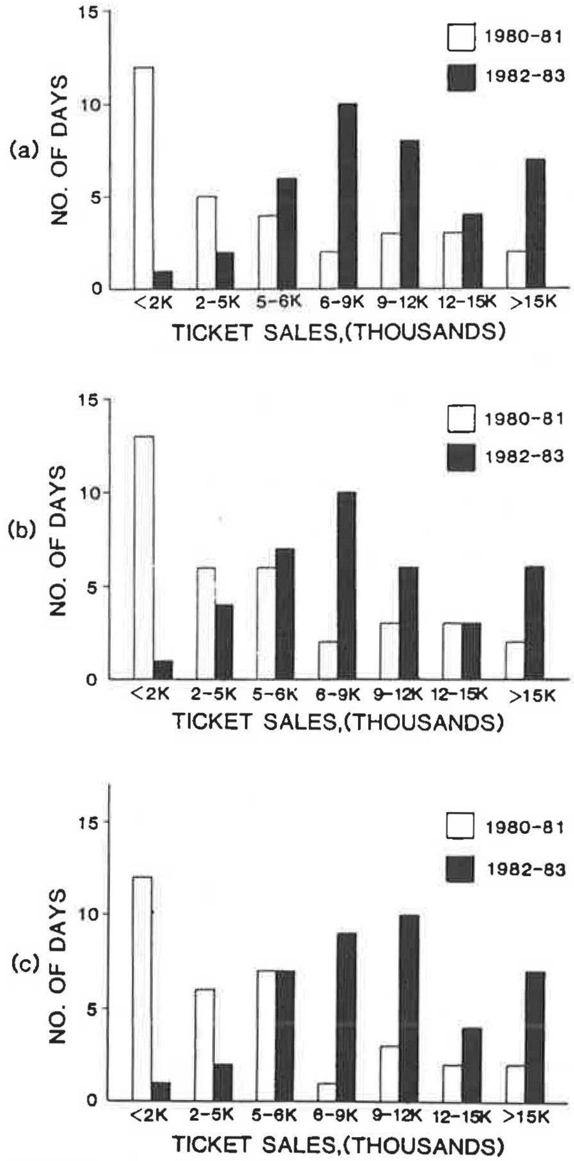

FIGURE 2 Number of days analyzed distributed by ski-lift ticket sales category for (a) 8-hr, (b) 1-hr a.m., and (c) 1-hr p.m.

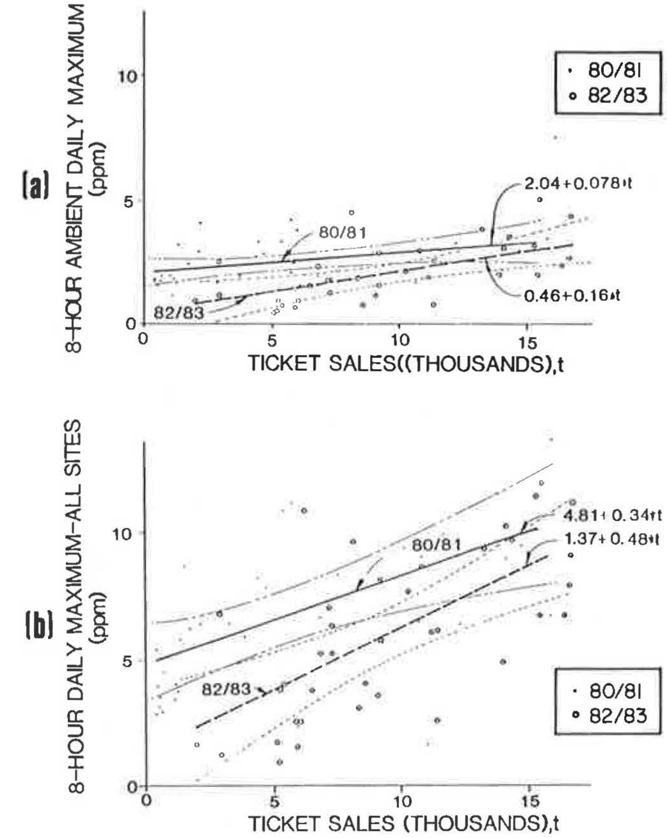

FIGURE 3 Daily maximum 8-hr CO concentration versus ticket sales for the 1980-1981 and 1982-1983 seasons: (a) ambient (Site C), (b) all sites.

pacity of the intersection. Plots similar to Figure 3b for the morning and evening 1-hr maximums showed the same tendency.

The responsiveness of the fully actuated signal is the probable cause for the air-quality improvements measured during periods of low to medium traffic volumes. Studies show that CO emission rates during accelerations are two to five times higher than average rates (4). By decreasing the number of vehicle stops, the new signal reduced the number of accelerations at the intersection and therefore lowered CO emissions. As conditions approached the capacity of the intersection, more vehicles were forced to stop and the number of accelerations climbed to preconstruction levels.

Cumulative frequency distributions for the three daily maximums are given by season in Figure 4. For the lower half of the 8-hr daily maximum distributions in Figure 4a, measurements from the 1980-1981 season tend to be 0.5 to 1 ppm higher than equivalent 1982-1983 values. The distribution of 1-hr evening maximums given in Figure 4c shows an average decrease in observed concentrations between the seasons of about 2.5 ppm over the range of results. The distribution of morning 1-hr maximums given in Figure 4b also shows about a 2.5-ppm improvement, but only for the upper quartile. Considering the far greater number of days sampled with high ticket sales during the 1982-1983 season, these results indicate that the Route 203 project helped improve overall air quality in the vicinity of the corridor. However, the graphs also show that state and federal standards were still being violated.

Plots of the seasonal maximums (i.e., the highest daily maximums recorded during the season) stratified by ticket sales are given in Figure 5. For both the morning and evening 1-hr maximums, measurements made during the 1982-1983 season were lower for five out of six ticket sales categories. For 8-hr maximums, four of the six categories showed improvement. On average, however, the improvements were no greater than the 18 percent reduction expected from newer vehicle emission controls.

In Figures 4 and 5, the number and size of 1-hr standard violations are greatest during the morning hours. However, these concentration peaks did not coincide with peak traffic volumes. Peak volumes occurred in the evening when either weather conditions or ski-lift closure forced skiers off the mountain at a single time. Based on traffic counts made on the days with highest ticket sales, evening 1-hr peak volumes were 35 to 55 percent higher than morning peaks.

There are a number of possible reasons why the highest CO concentrations did not coincide with the peak evening traffic volumes. A greater incidence of stagnant conditions during the morning hours was one

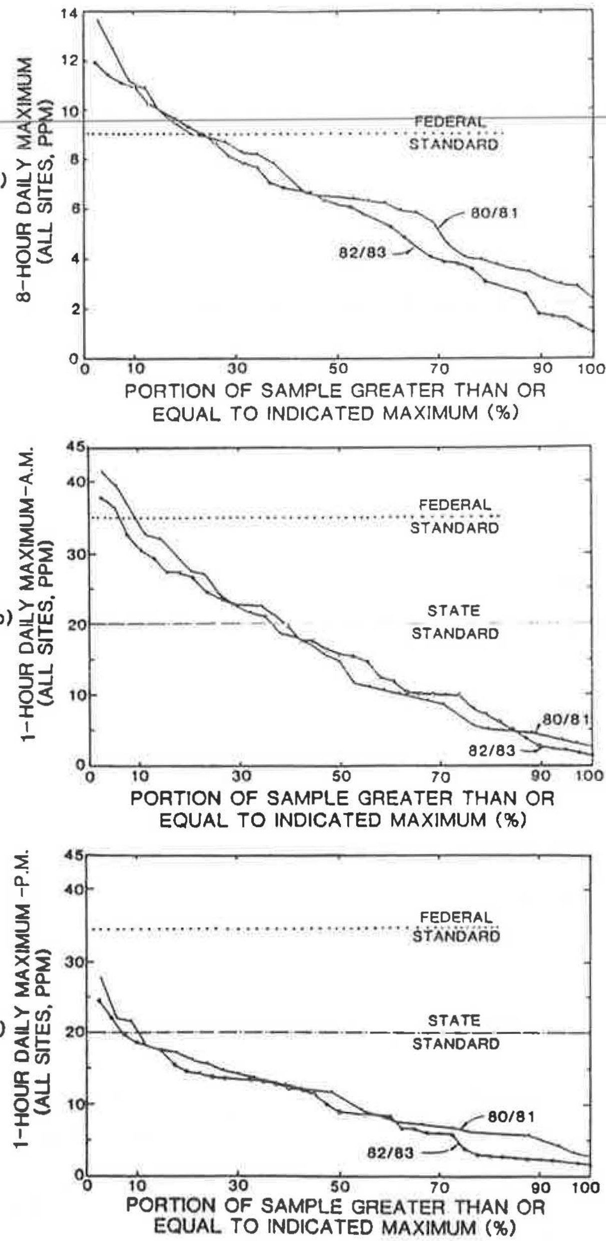

FIGURE 4 Cumulative frequency distributions of daily maximums for the 1980-1981 and 1982-1983 seasons: (a) 8-hr, (b) 1-hr a.m., and (c) 1-hr p.m.

possibility. However, the number of hours with wind speeds less than 2 m/sec was only 5 percent higher in the morning. A more likely reason concerns the effect of temperature on vehicle emissions. Colder morning temperatures cause considerably higher emissions for vehicles in the cold-start phase (i.e., first 505 sec). The proximity of many of the lodges and condominiums to the intersection meant that a large percentage of the morning ski traffic was in the cold-start phase. Fewer cold-start vehicles were expected in the evening because of the estimated 10-min travel time between the main ski-lift facility and the intersection.

A second significant contributing factor to the high morning concentrations is the average 4 percent grade of Route 203 near the intersection. Accelerations to 25 mph on a 4 percent grade can result in a fivefold increase in average vehicle emissions (4). In the morning, vehicles climb this grade, often slowing down or stopping to make the right-hand turn at the intersection. In the evening, the dominant downhill flow of traffic needs less effort to accelerate through the intersection and emissions decrease accordingly.

In Figure 6, the range of concentrations for each daily maximum are plotted by site for days with ticket sales exceeding 10,000. Seasonal high measurements for 1-hr concentrations made during 1982-1983 at the four intersection sites are lower than their respective 1980-1981 values. Again, however, the average reductions are no better than the 18 percent expected for the 1982-1983 vehicle fleet. Results for the 8-hr daily maximums in Figure 6a show improvements at Sites A and A1, but not at Sites A2 and B. Ambient concentrations measured at Site C show little or no improvement between the seasons.

The lack of significant reductions in ambient results and 8-hr seasonal maximums for the 1982-1983 season suggests that contributions from another pollutant source may have overshadowed the effects of the projected 18 percent reduction in vehicle emissions. Wood-burning stoves and fireplaces are standard features in the condominiums and cabins of Mammoth Lakes. Each condominium unit is stocked with a full supply of wood at the beginning of the ski season and restocked as the season progresses. According to studies by the Environmental Protection Agency (EPA), average CO emissions can range from 15 to 30 g/kg of fuel for fireplaces and 91 to 370 g/kg for stoves (5). At average burn rates used for certification testing by EPA, CO emission rates ranging from 2.5 to 5 g/min for fireplaces and 11 to 44 g/min for stoves can be expected. Composite idle emission rates used for modeling Route 203 vehicle emissions (described in a companion paper by Benson et al. in this Record) were approximately 8 g/min. The stoves and fireplaces are therefore likely to contribute to the Mammoth Lakes CO problem at a level comparable with that of transportation sources. These contributions will tend to mask emissions reductions achieved by transportation sources, especially over longer averaging times or at locations removed from primary transportation routes.

EFFECTIVENESS OF THE TRANSPORTATION CONTROL PLAN (TCP)

By the 1982-1983 ski season, construction of the bus stop shelters and staggering of ski-lift closing times were the only elements of the TCP implemented. It was hoped that the shelters would help increase ridership on the existing bus line and thereby reduce the demand volume on Route 203. District 9 personnel observed that the shelters were useful for indicating the location of bus stops otherwise obscured by roadside snowbanks. However, they also noted that patrons rarely used the shelters, preferring to wait outside. According to the owner of the bus line, weather was the only factor that had a significant influence on ridership. On days when chain controls were posted, ridership increased dramatically.

Daily passenger counts made by the bus operator for the 1981-1982 and 1982-1983 seasons were examined for evidence of increases in ridership. Because the shelters were not constructed until the summer of 1982, counts from the 1981-1982 season were considered representative of preconstruction conditions. The daily passenger counts averaged about 7.5 percent of the ski-lift ticket sales for both seasons. No evidence was found to indicate an increase in ridership.

A comparison of traffic volumes handled by the

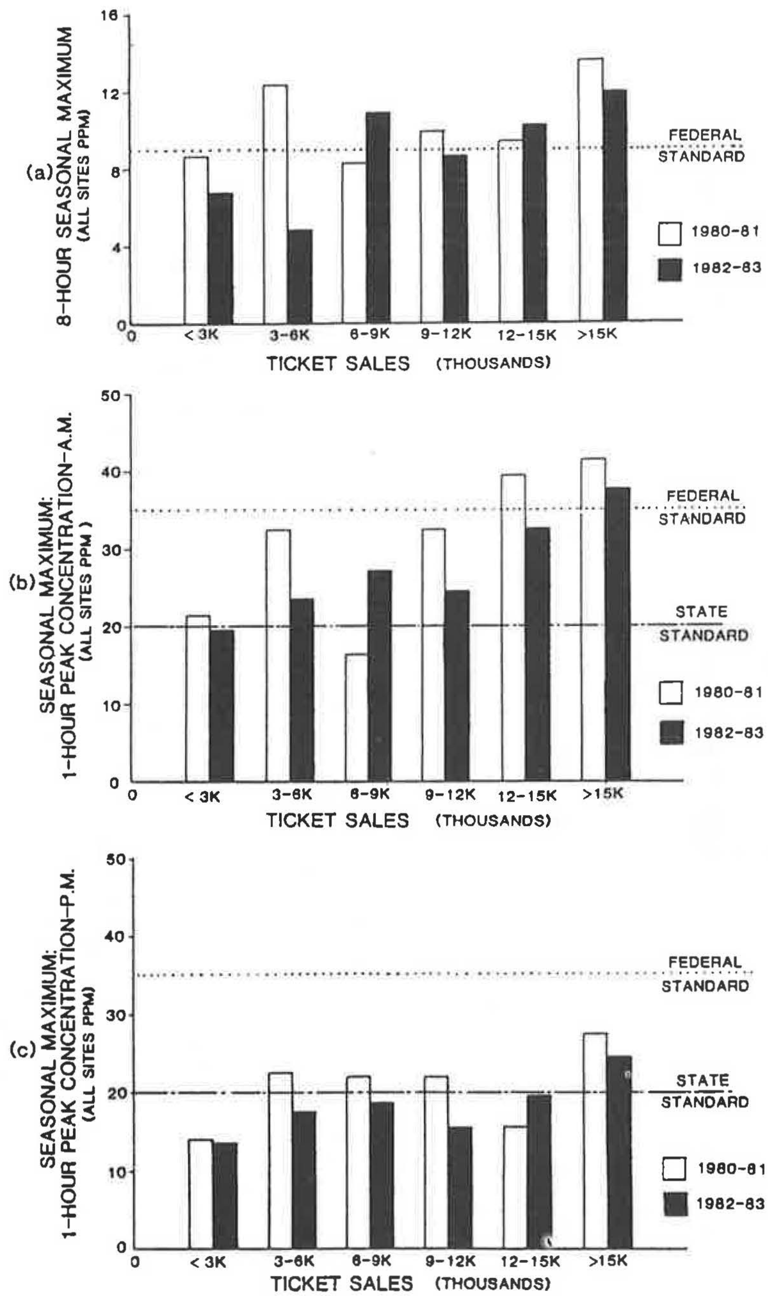

FIGURE 5 Seasonal maximum CO concentrations taken from all sites and distributed by ticket sales category for (a) 8-hr, (b) 1-hr a.m., and (c) 1-hr p.m.

intersection on the peak ski-lift ticket sales days for the 1980-1981 and 1982-1983 seasons was made to see whether fewer skiers were driving their own cars to the main ski-lift facility.

Ticket sales for the peak day in 1982-1983 were only 6 percent higher than those in the 1980-1981 peak, but the intersection carried approximately 20 percent more traffic during the 12-hr period from 7:00 a.m. to 7:00 p.m. If the shelters had a positive impact on bus ridership, it was apparently overshadowed by increases in private vehicle use motivated by the reduced traffic congestion.

The staggered closing of the ski lifts appeared to have no effect on evening peak-hour traffic volumes. Counts for the peak hour of 4:00 to 5:00 p.m. were up 33 percent from 1980-1981 levels on peak ski days. The added capacity of the route may have masked the positive effects of this operational improvement by accommodating residual demand not measured in the constrained 1980-1981 peak volumes.

Since the 1982-1983 ski season, several more elements of the TCP have been implemented. Caltrans has constructed a bus terminal at the main ski-lift facility, descriptions of transit service have been incorporated into promotional literature, and bus fares have been reduced by 50 percent.

Implementation of other major elements has been delayed, however:

- Expansion of the local road system has not taken place. Mammoth Lakes has incorporated since adoption of the TCP, so the county no longer has responsibility for implementation of this element. Further delay is expected as a result of a lawsuit and shortage of funds.
- Additional parking restrictions along Route

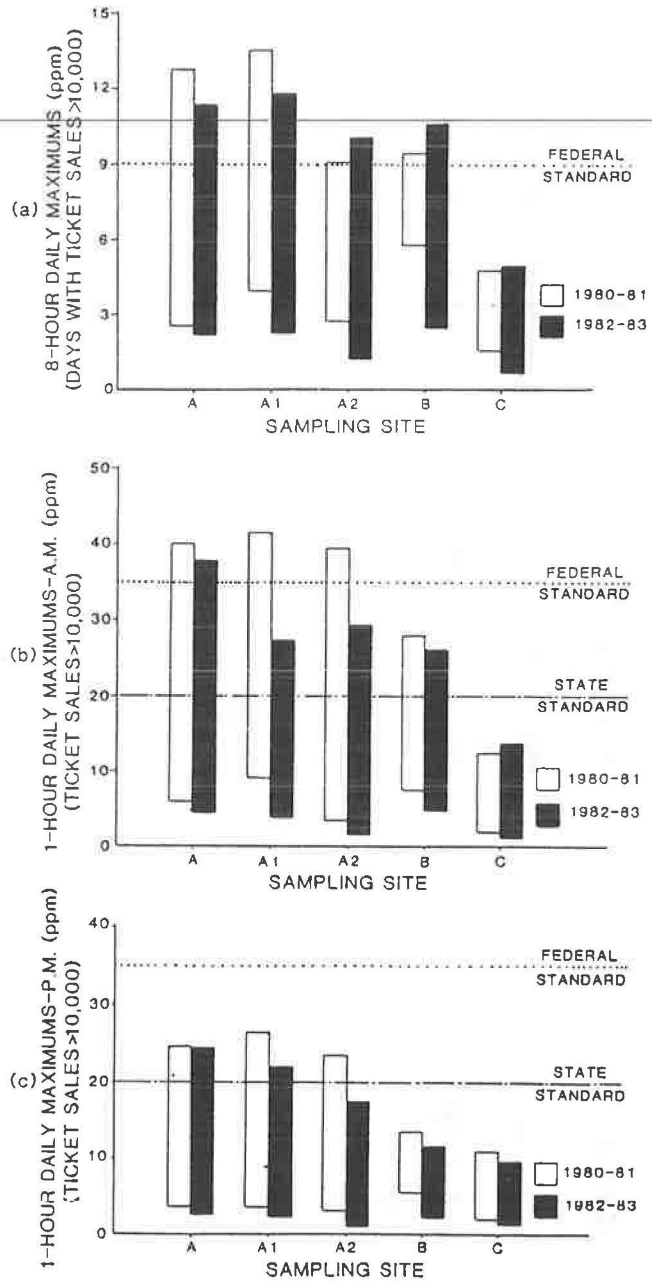

FIGURE 6 Range of daily maximum CO concentrations distributed by sampling site for (a) 8-hr, (b) 1-hr a.m., and (c) 1-hr p.m.

203 have not been made. These restrictions were meant to maximize use of developing transit facilities. Future transit development is uncertain at this time, however, because the previous bus operator is no longer in business. For the interim, the ski operator is providing scheduled service. An integrated transit plan has just been completed and is likely to be implemented as growth continues in the area.

• No ski runs have been lighted for nighttime use. It was hoped that this measure would help relieve peak evening traffic congestion.

• Additional development of ski facilities along Route 203 has not yet taken place. This includes construction of a ski-back trail, tram, and warming hut. Each of these access or egress points to the lift system were to be serviced by transit only.

Even though many elements of the TCP have not been implemented, CO concentrations at Mammoth Lakes have stabilized at an acceptable level. Measurements by the local air pollution control district show no further violations of state or federal CO standards after 1982 (6). Though not considered in the original TCP, a decision by the USDA Forest Service and the ski operator to redirect expansion outside the Route 203 corridor is probably responsible for this success. This was made possible by a fortuitous land purchase and cooperative trade arrangement between the Forest Service and a private-sector concern. By assuming responsibility for transit operations, the ski operator has also been able to fully integrate bus and ski-lift schedules. He has incorporated transit and walk-in access wherever facilities have been expanded and has not created additional parking.

CONCLUSIONS

The results of this study show that CO concentrations near the Route 203-Lake Mary Road intersection were reduced following construction of a comprehensive transportation improvement project. For low to medium traffic volumes, these reductions were due in part to the increased capacity of the intersection and the responsiveness of the fully actuated, three-phase signal. For traffic volumes approaching the capacity of the intersection, the reductions were due exclusively to the higher proportion of new vehicles with better emission controls in the post-construction vehicle fleet.

No significant improvements to ambient air quality as measured at Site C were seen. It is possible that increased CO emissions from wood-burning stoves and fireplaces masked projected reductions in vehicle fleet emissions. In any case, it was never expected that reductions in vehicle emissions brought about by relieving traffic congestion on a single route would have a measurable effect on areawide ambient concentrations.

No evidence was found in the 1982-1983 data to indicate that the bus shelters had a positive effect on transit use. The increased capacity of the route may have actually lured users away by decreasing congestion. Fortunately, subsequent expansion did not exploit this increased capacity.

In summary, experience has shown that transportation projects designed to improve traffic flow can also enhance air quality, but only if measures are taken to ensure that increased capacity is not exploited. In the case of Mammoth Lakes, expansion of facilities serviced by other roads relieved pressure on Route 203, helping to retain the reductions in traffic congestion created by the project. It is not clear whether the restrictions of the TCP or the potential for lost business (given a return to preconstruction congestion) provided the impetus for this decision. What is clear is that the environmental process forced consideration of problems that might have otherwise been overlooked, and that these problems were dealt with by both the private and public sector in a cooperative and constructive manner.

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Evaluation of the CALINE4 Line Source Dispersion Model for Complex Terrain Application

PAUL E. BENSON, WILLIAM A. NOKES, and ROBERT L. CRAMER

ABSTRACT

CALINE4, the latest version of the California Line Source Dispersion Model, is evaluated for use in complex terrain. Data from air-quality studies connected with a transportation improvement project along State Route 203 at Mammoth Lakes, California, are used for this purpose. A comprehensive tracer gas release experiment performed after completion of the project is described. Based on comparisons with the CALINE3 model and previous results for CALINE4 in flat terrain, model performance for receptors near the roadway in complex terrain is judged adequate for impact assessment purposes. Predictions for more distant receptors are much less reliable.

The California Line Source Dispersion Model, CALINE3 (1), is used throughout the country as a tool for evaluating the potential microscale air-quality impacts of transportation projects. The U.S. Environmental Protection Agency (EPA) has approved the model for general use with the provision that it not be used for studying projects in complex terrain (2). This restriction is made because of the assumptions on which the model is based.

CALINE3 uses a quasi-empirical Gaussian solution to the Fickian diffusion equation to model pollutant dispersion. This approach assumes a homogeneous wind flow field (both vertically and horizontally), steady-state conditions, and negligible along-wind diffusion. These assumptions can never be met exactly in any real-world application. However, for sites in relatively flat terrain and wind speeds above 0.5 m/sec, they are considered reasonable and yield answers that compare favorably with measured results (1). In this paper the extent to which these assumptions are satisfied for applications in complex terrain is examined.

A significant fraction of transportation projects is built in complex terrain. Because of difficulties

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in obtaining the requisite amount and quality of input data, three-dimensional, finite-difference models are rarely used for assessing air-quality impacts of these projects. Instead, a Gaussian model such as CALINE3 is applied. This approach is subject to a request from the reviewing agencies for a site-specific verification of the model. The California Air Resources Board carried out this type of verification study in 1981 for applications of CALINE3 in the vicinity of South Lake Tahoe (3). They concluded that the model predictions were slightly higher than observed values but were in good agreement with the measured hour-by-hour trends in air quality at most locations.

The South Lake Tahoe findings could not be extrapolated to other complex terrain sites, however. South Lake Tahoe's topography is representative of a large and relatively flat mountain basin. Projects were being proposed in much more complex locations. Questions remained about the model's ability to accurately predict impacts at such locations.

The planning and construction of a transportation improvement project along State Route 203 in the ski resort community of Mammoth Lakes, California, provided an opportunity to answer these questions. A comprehensive pre- and postconstruction monitoring program for carbon monoxide (CO) was conducted in connection with the project. The results of this work are described in a companion paper by Benson et al. in this Record. A series of experiments involving the release of tracer gas was also carried out after construction of the project.

The results of these experiments were used to evaluate the latest version of the California Line Source Dispersion Model, CALINE4 (4). CALINE4 is based on the same limiting assumptions as CALINE3 but contains improved algorithms for modeling vertical and horizontal dispersion. It has already proved superior to CALINE3 for flat terrain applications (4), and it was hoped that the improved dispersion algorithms would also enhance its performance in complex terrain.

EXPERIMENT PROCEDURES

The tracer gas release experiments were conducted during the winter of 1983-1984 along sections of State Route 203 and Lake Mary Road in Mammoth Lakes (Figure 1). The terrain is uneven, generally sloping downhill from the west. Strip commercial development is prevalent along Route 203, whereas the surrounding residential properties are interspersed among stands of mature conifers. Roadside snowbanks 1 to 6 m high are common during the winter months.

From the east boundary of the tracer release to the Lake Mary Road intersection, Route 203 has two lanes in each direction with a two-way left-turn lane between. From the Lake Mary Road intersection to the north and west boundaries, there is one lane in each direction with no median. Average daily traffic in the study area is 15,700 vehicles with a peak hourly volume on Route 203 of 3,100 vehicles.

Sulfur hexafluoride (SF_6) was used as the tracer gas. It is a highly inert gas, detectable at extremely low concentrations. SF_6 does not occur naturally and its presence in ambient air samples is negligible (5).

The SF_6 was released from two specially equipped 1970 Matador sedans. Each sedan had an on-off flow control switch mounted on the dashboard and a strip-chart recorder to monitor the flow status. The gas was contained in a cylinder secured in the trunk of the sedan. It was carried by copper tubing through the trunk floor to the tailpipe and released directly into the exhaust stream.

The tracer gas flow rates were checked before and after each test with a bubblemeter. The nominal flow rate, controlled by a needle valve, was 0.5 L/min. The measured flow rates typically varied no more than 20 percent from the nominal value over the course of a test. Tests were 2 1/2 hr in duration, with samples being taken only during the last 2 hr. The 1/2-hr delay was made to avoid sampling during the transient build-up phase of the release. A total of 13 tests were conducted at various times between 5:00 a.m. to 8:00 p.m.

The vehicles released SF_6 along the test section indicated in Figure 1. The SF_6 flow was turned off at each turnaround point as the vehicles left the test section. On the four-lane portion of the route, vehicles were assigned separate lanes. The distribution of the vehicles was controlled at a staging area by spacing departures at 4-min intervals. The drivers were instructed to try to maintain a speed between 30 and 35 mph. When stopped at the

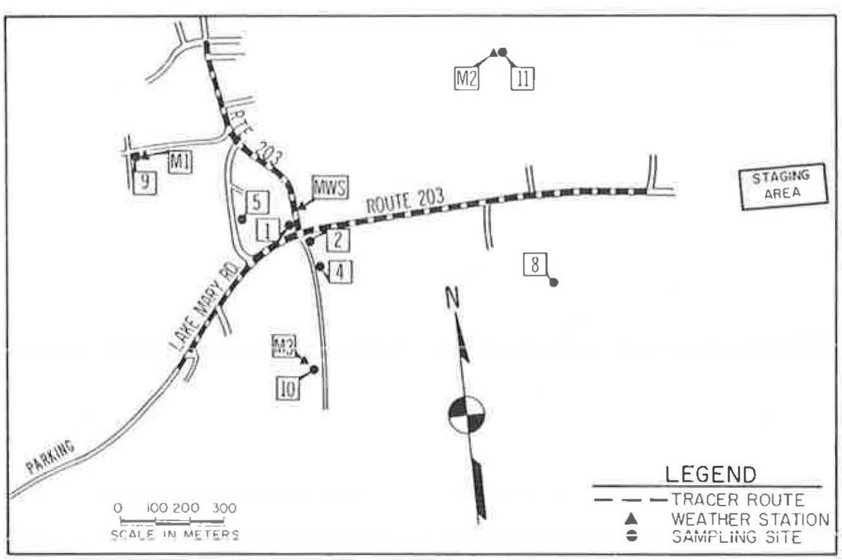

FIGURE 1 Tracer study sampling site location map.

intersection, the vehicles continued to release gas. Event markers recorded the location and duration of these releases on the strip chart.

Sampling sites were selected to represent three zones surrounding the Route 203-Lake Mary Road intersection. Their locations are shown in Figure 1. Sites 1 and 2 were located immediately adjacent to the intersection. These were designated as Zone 1 sites. The Zone 2 sites, Sites 4 and 5, were located 80 and 135 m from the intersection, respectively. Sites 8 through 11 ranged approximately 300 to 600 m from the intersection and were no closer than 190 m to the tracer release route. These were considered Zone 3 sites.

All samples were taken at a height of 1 m above the ground. They were collected in tedlar bags by using EMI AQS III samplers equipped with positive displacement pulse pumps. The samples represented 30-min integrated concentrations. They were analyzed on a Perkin-Elmer Sigma 2 gas chromatograph with electron capture detector. This instrument was calibrated with a Dasibi Model 1005 CE-2 flow dilution system and a National Bureau of Standards traceable cylinder of 5 ppm SF_6.

A meteorological tower 12 m high was located approximately 3 km east of the test course in an open area. It was equipped with a horizontal wind vane, two low-threshold (0.3 m/sec) cup anemometers, and a pair of self-aspirated temperature sensors. Information from this tower was used to estimate atmospheric stability by Golder's method (6).

A mechanical weather station was located in the northeast quadrant of the Route 203-Lake Mary Road intersection at a height of 10 m. Measurements from this device were used to determine wind direction and directional variability. Mechanical weather stations were also set up at Sites 9, 10, and 11 at a height of 1.5 m to measure surface winds. Wind speed was estimated as the average of these three measurements.

MODEL VERIFICATION

A statistical method developed through the National Cooperative Highway Research Program (7) was used to evaluate the performance of CALINE3 and CALINE4 on the Mammoth Lakes data. The method uses an overall figure of merit (FOM) based on six separate statistics. These statistics are defined as follows:

- S_1 = the ratio of the highest 5 percent of the measured concentrations to the highest 5 percent of the predicted concentrations,
- S_2 = the difference between the predicted and measured proportion of exceedances of a concentration threshold or air-quality standard,
- S_3 = Pearson's correlation coefficient for paired measured and predicted concentrations,
- S_4 = the temporal component of Pearson's correlation coefficient for paired concentrations,
- S_5 = the spatial component of Pearson's correlation coefficient for paired concentrations, and
- S_6 = the root mean square of the difference between paired measured and predicted concentrations.

Statistic S_1 measures the model's ability to predict high concentrations. Statistic S_2 measures how well the model predicts the frequency of exceeding an air-quality standard or threshold. Statistics S_3, S_4, and S_5 correlate the model's response to changing conditions with real-world response. Statistic S_4 considers changes over time (wind speed, atmospheric stability), whereas S_5 is associated with changes over space (source-receptor distance, topography). Statistic S_3 represents a combined measure of both factors. Statistic S_6 measures the overall error attributable to both modeling and measurement processes.

Each of the six statistics is converted into an individual FOM (F_1, F_2, F_3, etc.) based on a common scale from 0 to 10. An overall FOM is computed by weighting and summing the individual values as follows:

$$FOM = \{[(F_1 + F_2)/2] + [(F_3 + F_4 + F_5)/3] + F_6\}/3 \quad (1)$$

No standard value for FOM has been established to differentiate between "good" and "bad" model performance. A relative measure of model accuracy is used in this paper to compare CALINE3 and CALINE4 results in complex terrain and to contrast those results with performance in flat terrain.

Two graphical verification methods are also used to evaluate model performance. The first method is a scatterplot showing predicted versus measured concentrations. The second is a plot of relative error E_r by zone with E_r defined as

$$E_r = [(P - M)/(P + M)] * 100 \quad (2)$$

where P equals the prediction and M the measurement. E_r is a symmetric form of the residual error P - M normalized to 100 percent. It provides a convenient way to graph widely differing residual errors on a single scale.

Of the 13 tracer tests conducted during the study, only 4 were judged suitable for the verification analysis. The dates and times of these tests are shown in Table 1. Tests 1 and 4 were performed during downslope wind conditions, whereas Tests 2 and 3 coincided with upslope winds. These tests were selected because of their low wind speeds (below 2 m/sec) and lack of major discontinuities in wind direction over the 2 1/2-hr release period. SF_6 concentrations for the tests omitted from the analysis were usually low because of prevailing high winds or unsteady wind direction.

TABLE 1 Meteorological Data During Tracer Tests

Time	Wind Speed (m/sec)	Wind Direction (degrees)	Sigma Theta (degrees)	Temperature (°C)	Stability Class
Test 1, 1/12/84					
6:00-6:30 a.m.	0.47	330	5.0	–5.9	F
6:30-7:00 a.m.	0.36	330	5.0	–5.9	F
7:00-7:30 a.m.	0.40	330	5.0	–5.6	F
7:30-8:00 a.m.	0.39	330	5.0	–5.6	F
Test 2, 1/12/84					
12:00-12:30 p.m.	1.5	210	27.5	–0.4	C
12:30-1:00 p.m.	1.5	210	32.5	–0.4	C
1:00-1:30 p.m.	1.5	240	27.5	–0.5	C
1:30-2:00 p.m.	1.6	210	28.3	–0.5	C
Test 3, 2/7/84					
10:00-10:30 a.m.	0.67	120	40.0	8.9	C
10:30-11:00 a.m.	0.81	90	30.0	8.9	C
11:00-11:30 a.m.	0.88	135	25.0	9.9	C
11:30-12:00 p.m.	0.95	120	30.0	9.9	C
Test 4, 3/22/84					
6:00-6:30 p.m.	0.73	320	12.5	4.0	E
6:30-7:00 p.m.	0.68	315	12.5	4.0	E
7:00-7:30 p.m.	0.68	300	15.0	1.7	G
7:30-8:00 p.m.	0.78	310	7.5	1.7	G

Results from the four sampling periods for each test were examined for anomalous values. SF_6 concentrations near the intersection for the first sampling period of Test 1 were abnormally high. Levels of 43 ppb at Site 2 and 20 ppb at Sites 1 and 4 were 10 times higher than any other measurements made during the study. A review of 10-min integrated samples revealed a significant drop in concentrations at these sites during the first hour of Test 1 (Figure 2). The change was most dramatic during the

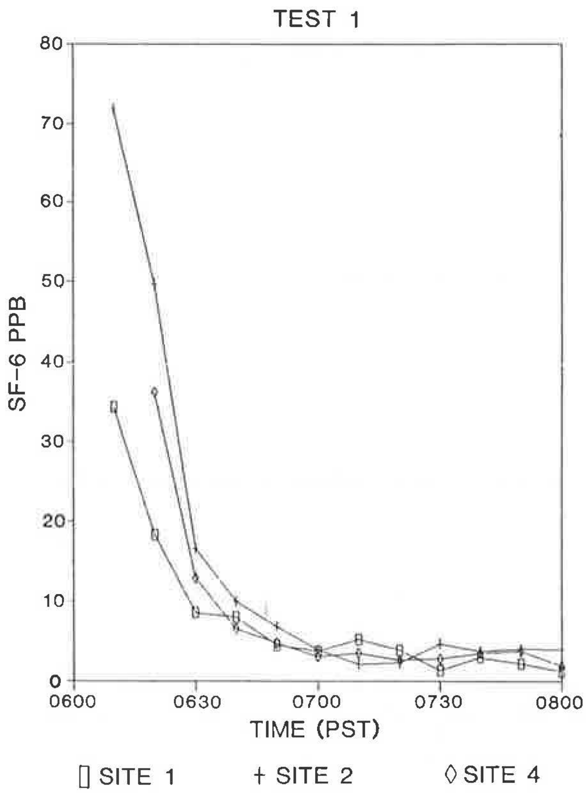

FIGURE 2 Test 1: 10-min integrated samples.

6:00-6:30 a.m. sampling period. Records were checked to see whether an accidental release of SF_6 might have occurred during the initial flow calibration procedure or the preliminary release period. No indications of an accidental release were found. Strip charts from the ground-level weather stations were examined for stagnant conditions sometimes associated with drainage winds in forested terrain (8-10). This may have caused the heavier-than-air tracer to create a "puddle" of SF_6 near the intersection. Although wind speeds were very low near the ground, the charts indicated that they were steady in direction and speed.

For some reason that is still not clear, SF_6 concentrations at Sites 1, 2, and 4 did not reach a reasonable state of equilibrium before the first 30-min sampling period of Test 1. The anomalous measurements were therefore removed from the verification data base because they did not conform with the model requirement for steady-state conditions.

The edited data base was used to develop FOMs for CALINE3 and CALINE4. A summary of the site-by-site results with zone and number of sampling periods noted is given in Table 2. Only downwind locations were used for computations. The threshold value for computing F_2 was 1.0 ppb SF_6.

The FOM results indicate superior performance by

TABLE 2 CALINE3 and CALINE4 FOMs for Mammoth Lakes Tracer Study

Site No.	Zone	No. of Periods	Model	F_1	F_2	F_3	F_6	Overall FOM
1	1	7	C3	1.6	9.0	8.0	0.1	4.5
			C4	6.3	9.3	8.0	4.2	6.7
2	2	8	C3	2.1	10.0	8.6	0.1	4.9
			C4	7.8	10.0	8.3	2.1	6.4
4	2	7	C3	2.0	9.6	8.5	0.1	4.8
			C4	7.9	9.6	8.2	3.1	6.7
5	2	8	C3	1.2	7.5	0.0	0.1	1.5
			C4	3.8	10.0	2.5	0.7	3.4
8	3	8	C3	3.2	8.6	5.2	1.7	4.3
			C4	1.3	8.3	2.9	1.2	2.9
9	3	8	C3	0.9	10.0	7.6	0.0	4.4
			C4	2.8	10.0	9.6	0.1	5.4
10	3	8	C3	8.2	7.9	4.7	1.5	4.8
			C4	1.3	8.2	0.6	1.2	2.2
11	3	8	C3	2.3	10.0	6.9	0.1	4.4
			C4	7.6	10.0	9.5	3.4	7.2

Note: C3 = CALINE3, C4 = CALINE4.

CALINE4 at six of the eight sites. At Sites 8 and 10, better performance by CALINE3 is indicated. As will be seen later, this is primarily due to more suspiciously high results from Test 1. The overall FOMs for CALINE3 and CALINE4, respectively, were 4.4 and 6.0 for Tests 1 and 4 (downslope) and 4.4 and 6.2 for Tests 2 and 3 (upslope). These results indicate that CALINE4 performed somewhat better than CALINE3 at the site with complex terrain.

FOM values based on previous studies of CALINE4 in flat terrain range from 6.4 to 6.8 (4). The overall values of 6.0 and 6.2 for this study fall just below that range. As indicated in Table 2, CALINE4 results for half of the sites (1, 2, 4, and 11) meet or exceed model performance in flat terrain. Results from Sites 5, 8, and 10 indicate extremely poor performance. Although there is no clear trend, the average FOM by zone decreases with distance from the intersection.

Scatterplots of CALINE4 predictions versus measured SF_6 concentrations at downwind sites are shown by zone in Figures 3 through 5. CALINE3 re-

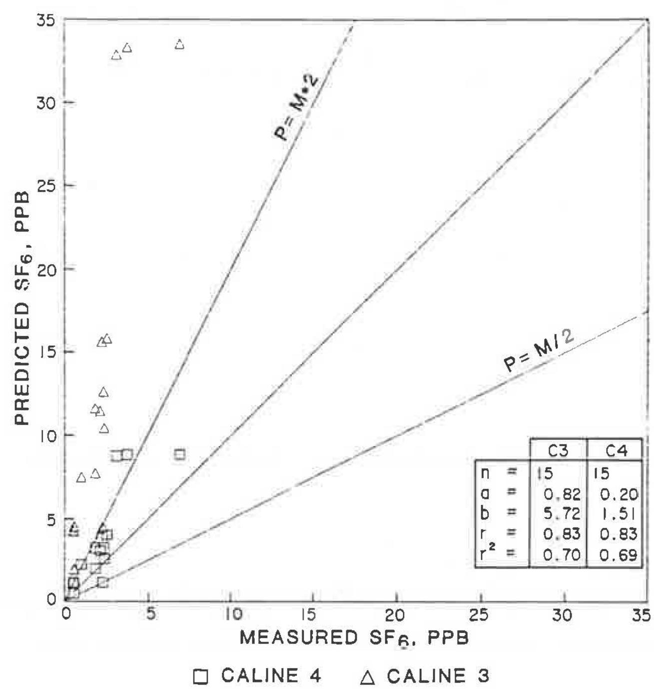

FIGURE 3 Zone 1 predicted versus measured SF_6 levels.

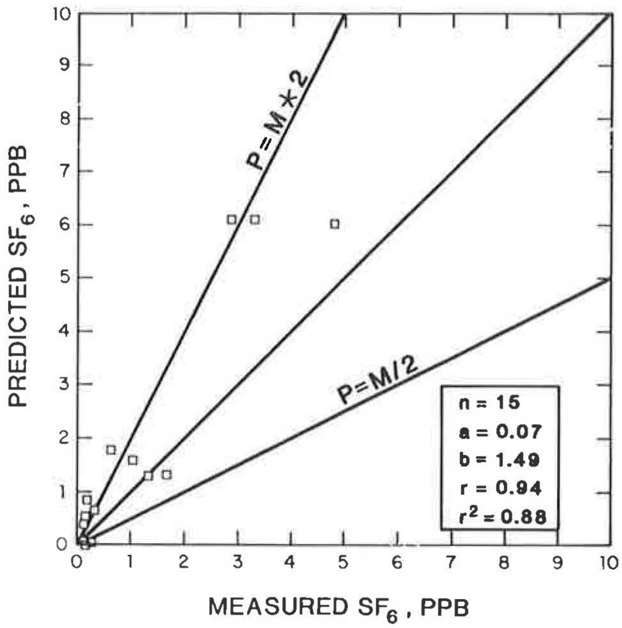

FIGURE 4 Zone 2 predicted versus measured SF_6 levels.

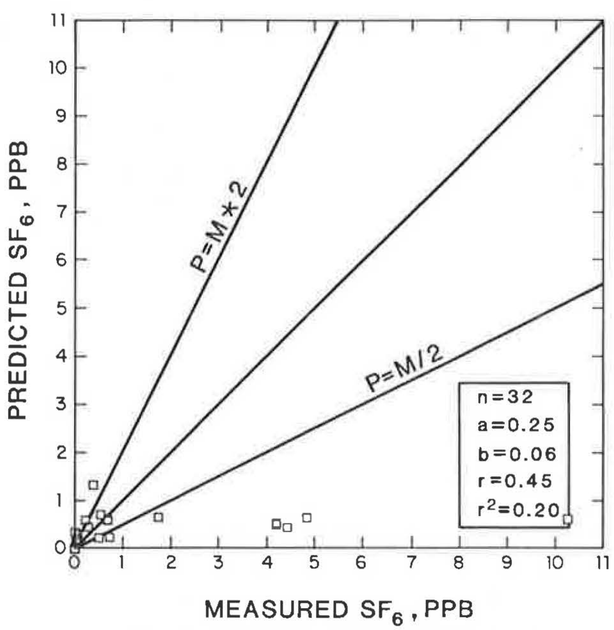

FIGURE 5 Zone 3 predicted versus measured SF_6 levels.

sults are included in the Zone 1 plot (Figure 3). A line of perfect agreement and factor-of-2 envelope highlight the results. Points falling inside the envelope represent predictions within plus or minus a factor of 2 of the measured concentrations, a frequently used minimum criterion for judging model performance. The number of points (n), intercept (a), slope (b), and correlation coefficient (r) for a linear least-squares regression are also given.

The number and magnitude of overpredictions by CALINE3 for Zone 1 sites indicate model performance inferior to that of CALINE4. Most of the overpredictions occur at wind speeds below the model's nominal limit of 1 m/sec. CALINE4 is better able to handle these conditions because of its ability to address wind meander through an improved horizontal dispersion algorithm. Nevertheless, Figures 3 and 4 also indicate an excess of overpredictions by CALINE4. Considering measured values of 0.5 ppb SF_6 and above, all the CALINE4 results that fall outside of the factor-of-2 envelope, approximately 30 percent of the total, are overpredictions. This is somewhat higher than the 13 percent and 22 percent reported for similar studies in flat terrain (4). The conservative pattern of overpredictions is similar, however.

The results for Zone 3 shown in Figure 5 indicate that model performance in complex terrain deteriorates with distance from the source. Considering only measured values equaling or exceeding 0.5 ppb SF_6, 7 of the 9 values (78 percent) fall outside of the factor-of-2 envelope. All of these are underpredictions. Five results measured at Sites 8 and 10 during Test 1 exceed an order-of-magnitude difference. Test 1 also contained the anomalous measurements for the first 30-min sampling period at Sites 1, 2, and 4. It is possible that the dense concentration of SF_6 measured at the intersection was transported downwind to Sites 8 and 10 in later sampling periods. However, even if these results are omitted from Figure 5, nearly two-thirds of the CALINE4 predictions still fall outside of the factor-of-2 envelope. The model is not able to predict concentrations at the distant Zone 3 sites with any reliability.

A plot of relative error versus zone (Figure 6) further dramatizes this point. The plot contains Test 1 results for Sites 8 and 10 but does not include any results for which either the predicted or measured values equaled zero. The differences in this latter case rarely exceeded 0.01 ppb. The factor-of-2 envelope is represented by the two horizontal lines at E_r = ±33 percent. A progressive deterioration in model performance by zone is clearly evident.

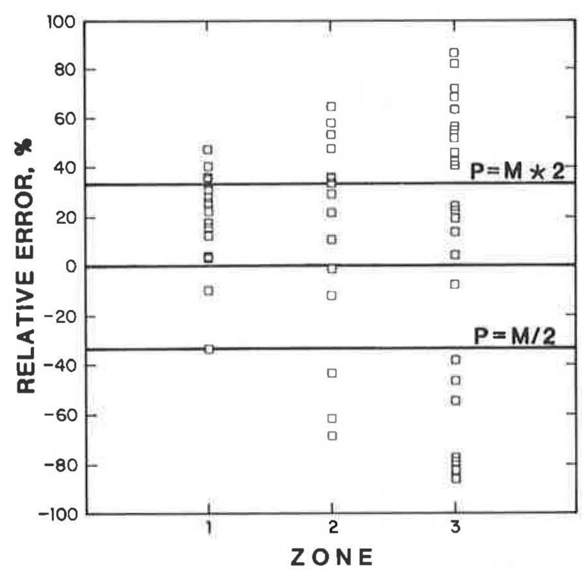

FIGURE 6 Relative error of predicted versus measured SF_6 levels versus zonal locations.

DISCUSSION OF RESULTS

It is obvious from the results of the verification analysis that CALINE4 has difficulty handling the temporal and spatial changes in meteorology that are commonplace in mountainous terrain. The model assumes that horizontal and vertical dispersion are adequately described by unimodal, normal distributions, and that wind direction is uniform over the study area. Real-world processes such as wind shear, channeling, and stagnation cause significant spatial variations in meteorology that clearly violate these assumptions. The model also assumes that the transport and dispersion processes have reached a steady-state condition. Periods of transition between flow regimes (e.g., downslope to upslope winds) cause changes in wind direction and speed that violate this assumption. Such transitions occur more often in complex terrain. Therefore, it is not surprising that the CALINE4 verification results for Mammoth Lakes fall short of results for similar studies in flat terrain.

There were, however, indications in the verification analysis that CALINE4 could be used successfully in complex terrain if the application was limited to sites immediately adjacent to the source. Model performance for the Zone 1 sites was comparable with performance in flat terrain because spatial and temporal variations in meteorology were less critical. Tracer gas released near the intersection had little time to disperse before reaching the Zone 1 sites. Concentrations were therefore heavily dependent on the emissions in the immediate vicinity of the intersection. Within this limited area, the effects of topography on meteorology were minimal. By restricting the analysis to a small area, CALINE4 performed better.

As a practical test of the model's ability to predict air quality impacts in complex terrain, model predictions for worst-case CO levels were compared with the highest levels recorded during a companion CO study (paper by Benson et al. in this Record). Sites 1, 2, and 4 of the tracer study were sampled as part of the companion study. The normal procedures recommended by Caltrans for assessing project-level air-quality impacts were followed. Emission factors for CO were generated by running the EMFAC6D program (California's version of MOBILE2) and adjusting results to the elevation of Mammoth Lakes by using EPA methods (11). Vehicle type distributions and traffic volumes were based on actual counts made during peak ski season weekends. Percent hot and cold starts was estimated for each leg of the intersection on the basis of observed travel patterns and a New Jersey Department of Transportation study (12). Recommended worst-case values for meteorology in mountainous terrain and worst-case wind directions were assumed (13). The maximum 1-hr CO concentration of 13.8 ppm sampled 1 km from the intersection was used as a background level (14,15).

The estimates were made for the morning time period (all of the highest measurements at each site were recorded between 7:00 and 10:00 a.m.). The intersection geometry was modified to accommodate four CALINE4 intersection links. Each of these links includes deceleration, idle, acceleration, and cruise components. Traffic and signal parameters were based on surveys conducted during the traffic counts.

Predictions of 1-hr averaged concentrations for CO at Sites 1, 2, and 4 were made. Predictions for a site in the same quadrant as Site 2 but about 5 m closer to the intersection were also made. This site, called A_1, was not included as part of the tracer study. These results and the highest measured values are summarized in Table 3. The measured 8-hr peak values are also included in the table. As can be seen, the predictions for the sites closest to the intersection (Sites A_1 and 1) agree quite well with the measured results. Underpredictions of approximately 10 ppm CO occur for the more distant Sites 2 and 4, however. The pattern of higher concentrations measured further from the intersection suggests the possibility of other significant contributing sources. Sites 2 and 4 were located on the edge of a motel parking lot. It is possible that idling cold-start vehicles or smoke from the nearby model chimney could have contaminated these samples. In any case, the performance of the model and the procedures for estimating the worst-case inputs are certainly reasonable for the receptors closest to the intersection.

TABLE 3 Measured and CALINE4-Predicted Worst-Case CO Concentrations for 1982-1983 Mammoth Lakes Air-Quality Monitoring Program

Site	One-Hour Predicted	One-Hour Measured	Eight-Hour Measured
1	27.5	26.1	10.2
2	24.1	36.4	11.4
4	19.4	29.3	10.7
A_1	29.4	30.5	11.0

The 8-hr peak concentrations were included in Table 3 to give an idea of the kind of persistence factor to be expected in complex terrain near a roadway with a pronounced traffic peak. The persistence factor, which is defined as the ratio of the 8-hr peak CO concentration to the 1-hr maximum, is normally assigned a value ranging from 0.6 to 0.7 (16). Because of the more frequent changes in meteorology typical of complex terrain, it appears reasonable to expect a lower persistence factor. The persistence factors computed from the results in Table 3 range from about 0.3 to 0.4. Applying the higher recommended persistence factors to the estimated 1-hr concentrations would have resulted in overestimates of the 8-hr average as high as 65 percent. This is the primary reason that the California Department of Transportation recommends the use of persistence factors derived from local data whenever possible (13).

CONCLUSIONS

CALINE4 model performance for adjacent receptors in complex terrain is not as good as that for similar modeling situations in flat terrain. However, the differences are not great when compared with the accuracy of many of the estimates that are used as inputs to the model. Predictions for more distant receptors are much less reliable. Model performance clearly deteriorates with distance from the emissions source. The model assumptions of steady-state, quasi-homogenous flow are obviously not satisfied for distant receptors in complex terrain.

On the basis of these findings, it is recommended that CALINE4 applications in complex terrain be restricted to receptors immediately adjacent to the primary source of emissions. For most project-level analyses, this restriction will not pose a problem because worse-case receptor locations are normally chosen at the right-of-way line.

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Tunnel Portal Noise

JIM O'CONNOR

ABSTRACT

In this paper the method, analysis, and results are presented of a study to determine the traffic noise field near and surrounding a highway tunnel portal. The purpose of the study was to determine how the increase in noise due to reverberations in a tunnel affects noise levels immediately outside a tunnel. An array of sound-level meters measured the traffic noise simultaneously at various locations near a tunnel portal. The results are given in terms of the statistical noise descriptors L_{10}, L_{50}, and L_{90}. Graphic plots of distance from the tunnel portal versus decibel level are presented. Measurements were taken on top and in front of the tunnel portal. The results indicate that for measurement sites on top of the tunnel, the drop-off in sound level is very abrupt and at 30 to 40 ft (9 to 12 m) behind the portal the traffic noise has diminished to the ambient noise levels of the surrounding area. For sites in front of the tunnel portal, the drop-off rate is less abrupt than that for the sites on top but still rapid and reaches normal free-field traffic noise levels at 60 to 70 ft (18 to 21 m) from the portal.

The Minnesota Department of Transportation (Mn/DOT) is constructing several short tunnels on I-35 in the city of Duluth. On top of the longest tunnel near the west portal, a scenic overlook to Lake Superior is planned. The Mn/DOT landscape architects wanted to know the width of landscaping required to prevent visitors from getting too close to the tunnel portal where they would be exposed to excessive traffic noise. The proposed overlook is shown in Figure 1.

The Mn/DOT Noise Unit studied the traffic noise near and surrounding an existing tunnel portal in the metropolitan area of St. Paul and Minneapolis. Two essential points were of interest. The first is concerned with the noise immediately above the tunnel. What is the sound level from a given volume of vehicles, and how does it vary with distance from the entrance? The second is concerned with the noise directly in front of the tunnel. How far down the highway does the tunnel noise affect the noise levels outside the tunnel and how do these noise levels vary with distance?

The tunnel selected for this experiment is shown in Figures 2 and 3 and is located on Trunk Highway 5 in St. Paul near Fort Snelling, a restored historical site. It is approximately 300 ft (91 m) long, 68 ft (21 m) wide, and 16 ft (5 m) high. It is of the single-barrel design and lined with tile.

MEASUREMENT METHODOLOGY

The basic approach to this study was to collect and evaluate traffic noise at a site where a well-traveled highway enters a tunnel. The highway passing through the tunnel used in this study has an average annual daily traffic of 45,000 vehicles. Twelve noise-measuring sites were chosen around the tunnel entrance, six on top of the tunnel and six in front of the tunnel at traffic elevation. The locations are shown in Figure 4. The field instrumentation for this study consisted of Bruel and Kjaer (B & K) 2209 and 2004 sound-level meters with 1/2-in. condenser pressure-type microphones and windscreens. The data were gathered with the method described in an FHWA report, Sound Procedures for Measuring Highway Noise (SPMHN) (1). The height of each microphone was 5 ft (1.5 m) above ground for both the top and front tunnel locations (see Figure 5). The microphones in front of the tunnel were located 23 ft (7 m) away and perpendicular to the median of the traffic at 7, 20, 32, 57, 107, and 160 ft (2, 6, 10, 17, 33, and 49 m) north of the north tunnel portal. The microphones on top were 7 ft (2 m) north and 2, 10, 15, 20, and 70 ft (0.6, 3, 4.5, 6, and 21 m) south of the north tunnel portal. Sites 1A, 6, and 7 were measured on a different day than the other sites. Experience has shown that when the distance between source and receiver is less than 50 ft (15 m), changes in meteorological conditions will not affect the overall trend in the measurement results. The 2 days used for the measurement period were both similar in meteorological and traffic conditions. The highway approaching and leaving the tunnel has no significant grade or curve.

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DATA ANALYSIS

The measured noise values were determined in the form of statistical descriptors. Of particular interest were L_{10}, L_{50}, and L_{90}. The 95 percent confidence limits were determined as described in SPMHN (1). The values are presented in Table 1. The column labeled Corrected L_{10} in Table 1 represents the middle value within the interval of the confidence limits. Graphic plots were made of decibel level versus distance from the tunnel portal.

RESULTS

The graphic plots shown in Figure 6 indicated that the sites on top of the tunnel (i.e., Sites 1, 2, 3, and 4) have a very abrupt drop-off rate in noise level. Increased noise at the tunnel portal due to reverberation within the tunnel for these sites is insignificant beyond 30 to 40 ft (9 to 12 m). Figure 6 also shows that the sites in front of the tunnel

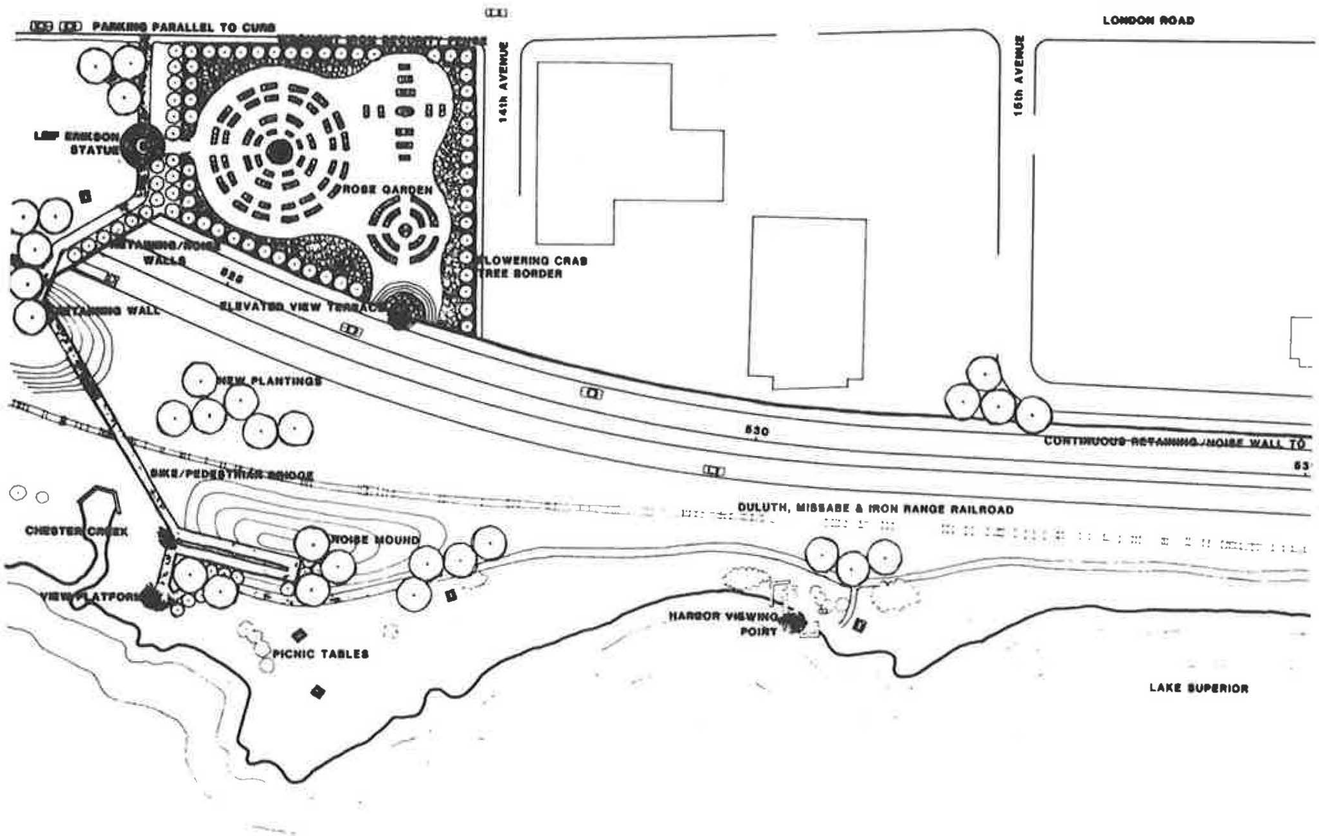

FIGURE 1 Proposed scenic overlook.

FIGURE 2 Test tunnel, view 1.

FIGURE 3 Test tunnel, view 2.

(i.e., Sites 5, 6, 7, 8, 9, and 10) have a drop-off in noise level less abrupt than that of the sites on top of the tunnel, but still rapid. Increased noise at the tunnel portal due to reverberation within the tunnel for these sites is insignificant beyond 60 to 70 ft (18 to 21 m). The noise levels and site descriptions are given in Table 1. For measurement sites in front of the tunnel, the variability of the traffic noise increases with distance from the portal. For the sites on top of the tunnel, the variability of the traffic noise decreases with distance from the portal. This is indicated by observing the values in the column labeled L_{10}-L_{50} in Table 1. Table 1 also indicates that Site 5 is under the influence of the tunnel noise reverberation. Sites 9 and 10 are beyond the effects of the tunnel noise reverberation. The difference in L_{10} between Sites 5 and 9 is approximately 7 dBA. The tunnel noise reverberation increases traffic noise by 7 dBA. By observing the L_{90}-values in Table 1, it can be seen that at Site 5 the level is above 83 dB 90 percent of the time. At Site 10 it is above 74 dB 90 percent of the time.

CONCLUSION

The increase in noise at a tunnel portal due to reverberation within the tunnel decreases rapidly for receivers on top of the tunnel with distance behind the portal. An acceptable traffic noise-mitigation technique may be a band of dense foliage 40 to 50 ft (12-15 m) wide, which would prevent receivers from approaching the noisy area directly behind the portal.

It may be concluded that the L_{10}-L_{50} difference (noise variation) decreases as the distance behind a tunnel portal increases when the listener is on top

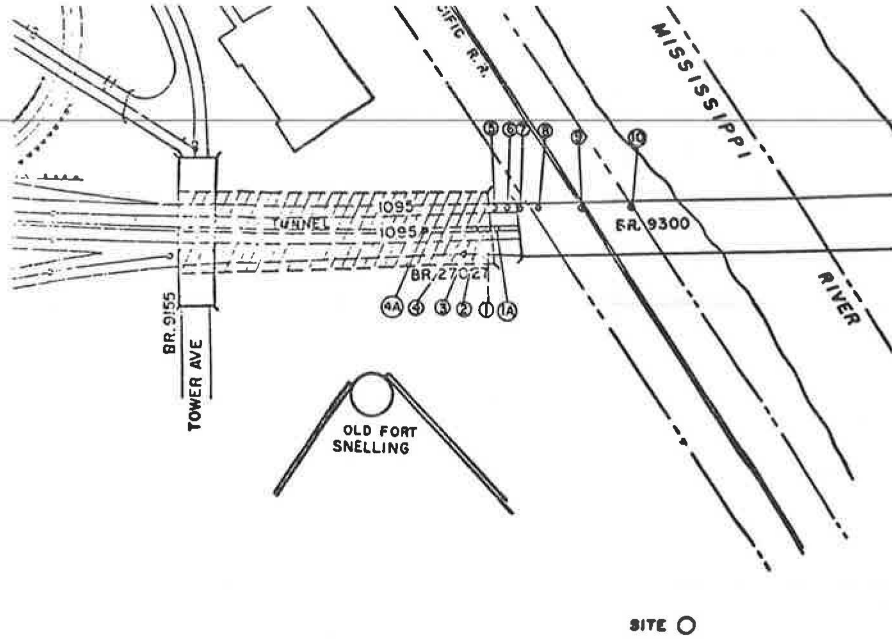

FIGURE 4 Measurement sites.

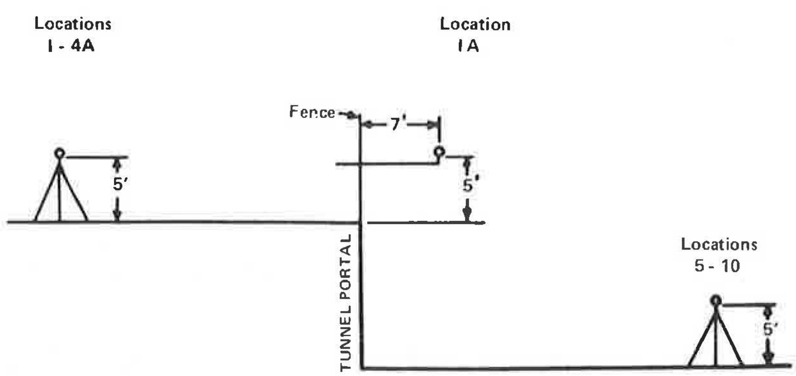

FIGURE 5 Instrument set-up.

TABLE 1 Site Location, Sound Pressure Levels, and Traffic

Location and Site	L_{10} (dBA)	95% Confidence Limits	Corrected L_{10} (dBA)	L_{50} (dBA)	L_{90} (dBA)	L_{10}-L_{50} (dBA)
On top of tunnel						
1A[a,b]: 7 ft north of north portal	85	+3 1/2 −1 1/2	86	79		7
1: 2 ft south of north portal	79	±2 1/2	79	73	68	6
2: 10 ft south of north portal	73	+2 1/2 −1 1/2	73 1/2	69		4 1/2
3: 15 ft south of north portal	69	+2 1/2 −1 1/2	69 1/2	66	62	3 1/2
4: 20 ft south of north portal	67	+2 1/2 −1 1/2	67 1/2	64	61	3 1/2
4A: 70 ft south of north portal	64	±2 1/2	64	60		4
West walk of Mississippi River Bridge						
5: 7 ft north of north tunnel portal	91	±1 1/2	91	87	83	4
6[a]: 20 ft north of north tunnel portal	88	±2 1/2	88	83	77	5
7[a]: 32 ft north of north tunnel portal	85	+2 1/2	85 1/2	81	73	4 1/2
8: 57 ft north of north tunnel portal	84	+2 1/2	84 1/2	81	77	3 1/2
9: 107 ft north of north tunnel portal	84	+2 1/2 −1 1/2	84 1/2	80	76	4 1/2
10: 160 ft north of north tunnel portal	83	+2 1/2	83 1/2	79	74	4 1/2

Note: Average speed (mph): automobiles, 48.1; standard deviation, 5.4; trucks, 46.2; standard deviation, 6.8.

[a]These sites were measured on a different day than the other sites.

[b]This measurement was made by holding the microphone, mounted on a range pole, out over the top of the tunnel.

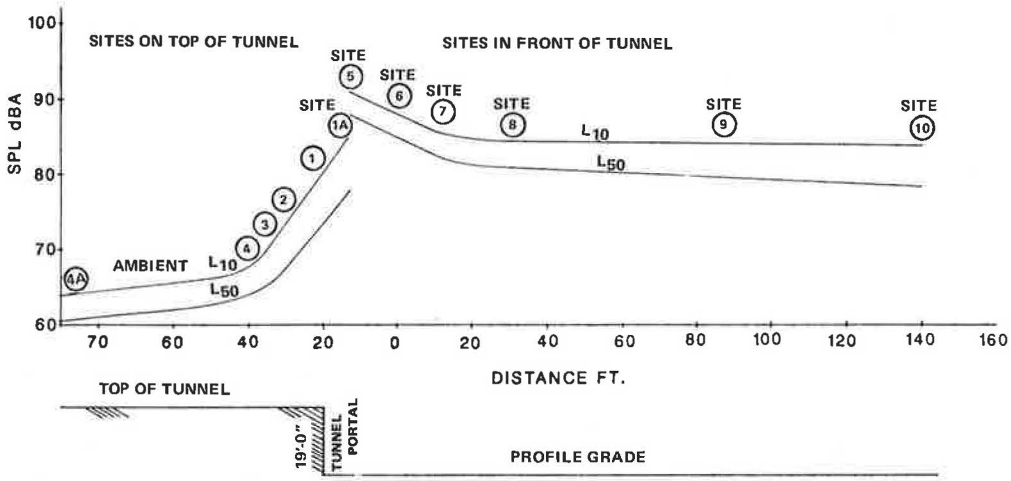

FIGURE 6 L_{10} and L_{50} sound level versus distance.

of the tunnel until ambient conditions exist. When the listener is in front of the tunnel and adjacent to the traffic flow, the L_{10}-L_{50} difference increases as the distance from a tunnel portal increases until the free-field traffic noise exists. When the L_{10}-L_{90} value at the free-field site is compared with the L_{10}-L_{90} value from just immediately outside the portal, it may be concluded that even though the variability of the noise decreases in the tunnel, the noise pollution level (L_{NP}) (2) increases because of the large increase in the L_{50} inside the tunnel. It may be concluded that the increase in traffic noise due to reverberation within a tunnel is of no particular consequence to receivers 60 to 70 ft beyond the portal.

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Publication of this paper sponsored by Committee on Transportation-Related Noise and Vibration.

Traffic-Related Noise as a Factor in Eminent Domain Proceedings in Florida

WIN LINDEMAN

ABSTRACT

Traffic-related noise has become an increasingly important factor in eminent domain proceedings in Florida. The nature of the eminent domain process in Florida is explored as it relates to the Florida Department of Transportation and traffic noise. Through the examination of five case studies, the impact of noise on condemnation cases is highlighted. On the basis of the developing case histories, it can be concluded that noise specialists, attorneys, and appraisers alike need to be prepared to deal with noise in a learned and professional manner.

Traffic noise is a fact of everyday life, whether one lives in Alaska or Florida. However, the liability of the state to compensate a property owner for traffic-related noise damages varies from state to state. It is the purpose of this paper to point out how traffic-related noise damage is addressed as part of the eminent domain proceedings in Florida.

EMINENT DOMAIN PROCESS IN FLORIDA

To better understand the nature of eminent domain proceedings in Florida, and how noise is involved, a brief review of the process is necessary. Eminent domain is defined as "the power of the sovereign to take property for public use without the owner's consent" (1,pp.1-7). In eminent domain proceedings, "noise is treated as consequential damage," which means it is a direct result of the actions of the condemnor (2,p.936-N2), although in Florida it may or may not be compensable. Sometimes noise is also treated as proximity damage. This is a damage resulting from the nearness of the property to the noise source. This could be the case if a highway location were moved next to a hospital's front door without actually touching the building, even though some of the land may have been taken from the hospital. This is not considered as a direct taking. The Florida constitution is structured so that Florida is a "taking" state and not a "damage" state. This means that the state pays only for the taking of property and not for damages to those properties. However, Figure 1 shows that this principle can vary once the state passes the test of severe damage, which the courts treat as a taking. To date, the Florida courts have held that "alleged damages to a resident's property not actually taken for highway, resulting from increased noises, dust and vibrations, were not compensable" (3). Florida is in a position where the courts have ruled that noise does not constitute a taking and therefore is not compensable, yet noise is frequently an issue in condemnation actions in Florida.

If property is required for a state highway project in Florida, the Department of Transportation (DOT) will establish a fair value for the parcel (or portion thereof) of land needed, using the appropriate appraisal technique. The appraisal will become the basis for an offer to the property owner.

Florida Department of Transportation, 605 Suwannee Street, Tallahassee, Fla. 32301.

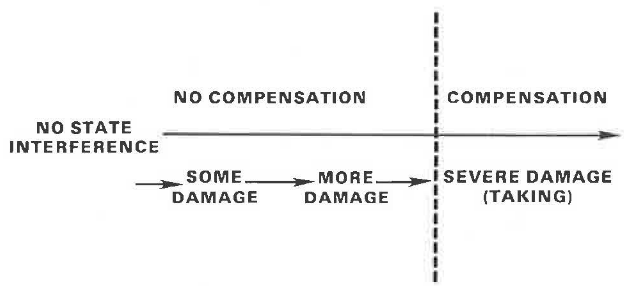

FIGURE 1 Severe damage test.

Should the property owner not be satisfied with the offer, the Department may, under Florida Statute Chapter 74, "take possession and title in advance of the entry of final judgment" (4,pp.31-270). This is done by filing a declaration of taking. Once the declaration is served (which includes a good faith estimate of value) and an order of taking is granted by the court, "the fair estimate value must be deposited in the registry of the court. The purpose for making a good faith estimate is to fix a basis for withdrawal by the owner from the deposit, so that the owner will have the use of the money as the petitioner (DOT) has the use of the land" (4).

After the order of taking but before the trial, numerous opportunities exist for both the property owner and the DOT to alter their stance and reach a mutual agreement. To ensure that the property owner is on an equal basis with the condemnor (in this case DOT), Florida law requires that DOT "must pay the owner's attorneys' fees and necessary expenses incurred in his defense of the proceedings" (4). This also holds true for appellate actions. The court will establish what fees and expenses are necessary and appropriate. It is during this time frame that DOT has normally resolved noise issues and settled with the property owner. In two major suits, however, the case went to trial and through the appeal process. The results will be discussed later in this paper.

PROPERTY INTERESTS SUBJECT TO CONDEMNATION

When the entire parcel is taken (total take), there usually is no difficulty with noise as an issue. It is when the Department takes a part of the property (partial take) that noise has become a significant issue. This may result in the awarding of severance damages in addition to the value of the property taken. The amount of damages allowed (or awarded if established by the court) is generally determined on the concept of "before and after, which poses the question: What was the value before the taking; and what is now the market value after the taking?" (4). One way to mitigate severance damages is to provide the "cost to cure," which restores the remaining property and all improvements to their original use and value. To use this approach, the first step is to establish the total value of the damages. Then, after the damages have been determined, a method to "cure" the damage is proposed. If the cost to cure the damage is less than the estimated damage, this mitigation method may be used. This approach has frequently been used when noise is one of the issues in a condemnation proceeding.

Inverse condemnation suits usually occur when a property owner believes that his property has been damaged even though none of his property was taken by lawful actions of the DOT. Far more cases of inverse condemnation involve a physical invasion and the courts more readily find a taking to have occurred when there has been a physical invasion. But the real test is found in the degree that the owner is deprived of the use and enjoyment of his property by whatever means, "physical invasion or not" (4).

One of the important distinctions between a typical taking and inverse condemnation is in the financial arrangement. "The owner's reasonable costs and attorneys' fees are taxable against the governmental agency if the inverse condemnation action is successful. If the owner is unsuccessful in maintaining the inverse condemnation action, costs are taxable against him as in other civil actions" (4).

CASE STUDIES OF NOISE IN FLORIDA EMINENT DOMAIN PROCEEDINGS

Five cases will be examined to see how the courts and DOT have addressed the issue of highway traffic-related noise as part of the eminent domain process in Florida. The case studies will be listed in chronological order (rather than by category) to illustrate how the issue of noise has varied over time.

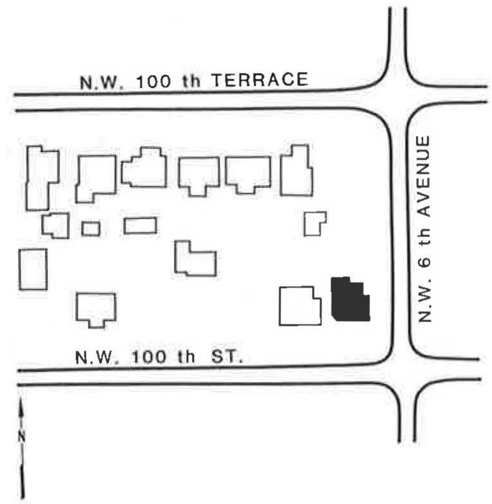

FIGURE 2 Northcutt property before take.

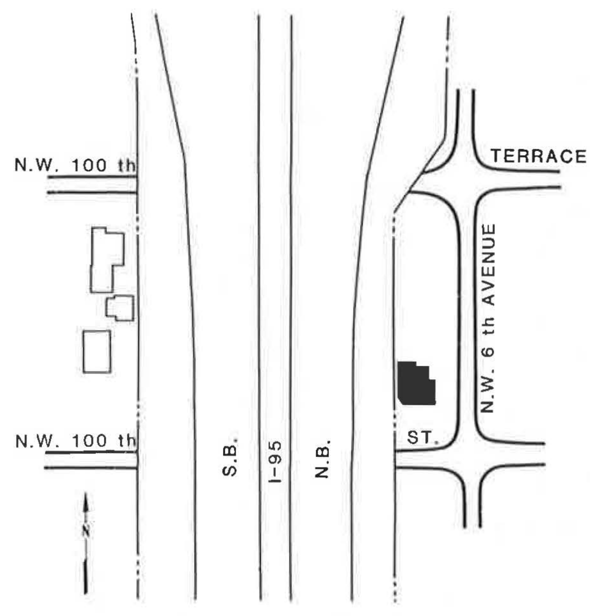

FIGURE 3 Northcutt property after take.

Northcutt v. State Road Department (3)

In the case of Northcutt v. State Road Department (1968), the Northcutt family filed an inverse condemnation suit against DOT, alleging damages to their residential property not actually taken for highway construction (Figure 2). They believed that the increased noise, dust, and vibration changed their quiet residential side street to a haul route during construction. Following the construction activities, the close proximity of Interstate 95 (Figure 3) caused structural damage to their house and the traffic caused "excessive shock waves, vibrations, and noises, at all hours of the day and night which impaired their health and caused them to lose sleep, become ill and nervous and deprived them of the use and aesthetic beauty of their property, causing it to lose its value for residential purposes so that it cannot be sold or financed for any use or purpose" (3).

The Third District Court of Appeal of Florida upheld the lower court's ruling that the alleged damages were not compensable. The court noted that "there must generally be a trespass or physical invasion, since (the Florida) constitution does not provide compensation for mere damage" (3). The court indicated that "low flying jet aircraft with their great speed and noise have brought about serious legal problems for adjacent land owners" but the "plight of the property owner in this case is not the same . . . but is indistinguishable from that of thousands of their fellow country men whose homes abut highways and railroads and who endure the noise without complaint" (3). Had the landowner shown that he was "severely" damaged, the outcome might have been different.

Department of Transportation v. West Palm Beach Garden Club, et al. (5)

The next case involves the Department of Transportation v. West Palm Beach Garden Club, et al. (1977). In this case, the DOT was ordered by the Circuit Court of Palm Beach County to pay $644,275 for the value of the land taken for the construction of Interstate 95 and $1.7 million in severance damages. The DOT appealed this case on the basis of six different points of law related to eminent domain. Three of those points related to noise because $1,477,500 of the jury award for severance damages involved the construction of a noise barrier wall.

The property taken involved a small portion of a city park (Dreher Park) (Figure 4) that the owner claimed as a place of quietude and passive use. Citing the famous Dennison case in New York, the owner's attorney was successful in convincing the jury that the construction of a noise barrier was necessary to preserve the usefulness of the park.

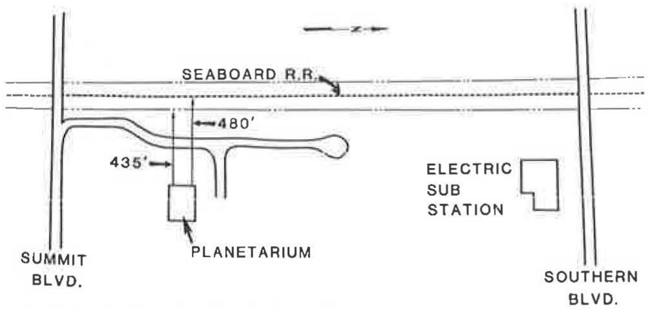

FIGURE 4 Dreher Park before take.

On appeal, the DOT pointed out that "mere highway noise as such, not coupled with a physical invasion or trespass, is not compensable in a condemnation proceeding" (5). They also noted that the "award of severance damages for (the) purpose of curing noise from (a) highway by constructing (a noise barrier) wall to preserve (the) tranquility of (the) park was (in) error, in view of (the) indication that the noise increase did not preclude use of (the) park as a park and that the park was not a secluded and peaceful park" (5). Finally, the DOT pointed out that noise from the highway would not damage the use of the zoo, science museum, and planetarium within the park and a nearby golf course because they "were not substantially deprived of their beneficial use" (5).

The Fourth District Court of Appeal reversed the lower court's decision regarding the severance damages on July 26, 1977. Judge Letts, in writing the reversal opinion, noted factors that the jury appeared to overlook. He noted that the park land had originally been sold to the city by the state of Florida for $100 and that the city was told at the time of the sale that a major highway was to be built through that location. The city converted this parcel of raw land of swamp, muck, and sand into an attractive, active park. In 1952 the city gave the state some of the land back for use in construction of a highway. At a later date an additional 150 ft of linear park land was condemned for the construction of I-95. Judge Letts noted that the city did not identify noise as a damage factor in the beginning of the condemnation suit. As a matter of fact, the city was very supportive of early completion of I-95 in this area and urged the DOT to forego any additional environmental impact studies that might delay the project.

The judge pointed out that "the bulk of the $1,700,000 award was to build a wall on land not taken and on which there was no physical invasion or trespass" (5). In considering the noise increase to the park caused by I-95 traffic, Judge Letts noted that this "is no more of a 'taking' than has been inflicted on countless tens of thousands of Florida residences . . . whose occupants endure the consequences of endless traffic noise. . . . The damage to Dreher Park is no different in kind from that suffered by anyone else similarly situated" (5). This again points out the importance of the landowner's showing "severe" damage by the state.

The city tried to portray Dreher Park as a passive park where quiet was important and the noise from the highway would destroy this tranquility. The court questioned how this could be at a park "one and one-half miles away from touchdown, next to a screaming jet glide path for a major airport, six blocks from US #1, bounded on the north and south by major arteries, bisected by a third, and bordered by the Seaboard Airline Railroad tracks. Moreover, the park itself has a zoo, a museum, ball fields, model airplane club, and immediately to the north, an electrical substation" (5) (Figure 5).

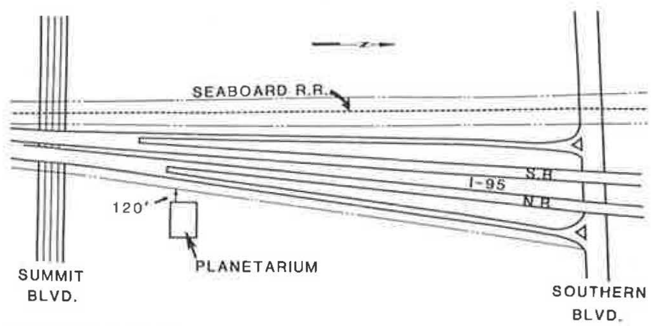

FIGURE 5 Dreher Park after take.

On the basis of the evidence presented, the entire severance and cost-to-cure award of $1,700,000 was reversed and sent back to the trial court for review. The outcome was that the severance damages (cost to cure) were reduced from $1,700,000 to $72,500.

Department of Transportation v. Elmer R. Harjula, et al.

In the case of State of Florida Department of Transportation v. Elmer R. Harjula, et al. (1984), the DOT sought to acquire a total of 19,284 ft^2 of property from the Garden Lakes Homeowners Association, Inc. (Figure 6). This land, referred to as "the common areas" (shared by the members of the homeowners association), is part of a large condominium property. The property was needed for the construction of I-95 in northern Palm Beach County and the expansion of Military Trail, a local arterial (Figure 7).

During the environmental assessment process, a noise study was conducted that indicated that there could be noise impacts in the area of the subject property. The need for abatement was explored and a noise barrier wall was recommended. A subsequent noise analysis reversed the previous study and stated that abatement was not necessary. As final design was approached and right-of-way takings proceeded, the issue of noise and noise abatement was raised by the attorneys for the homeowners associa-

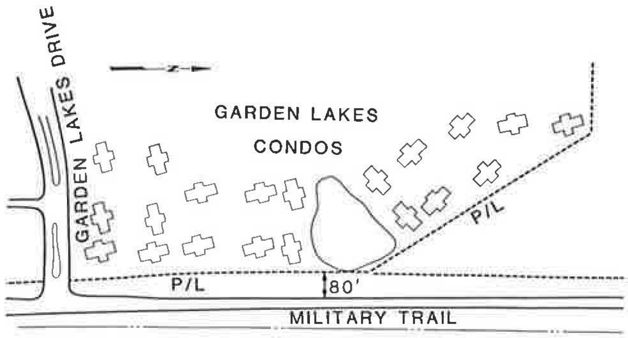

FIGURE 6 Garden Lakes condos before take.

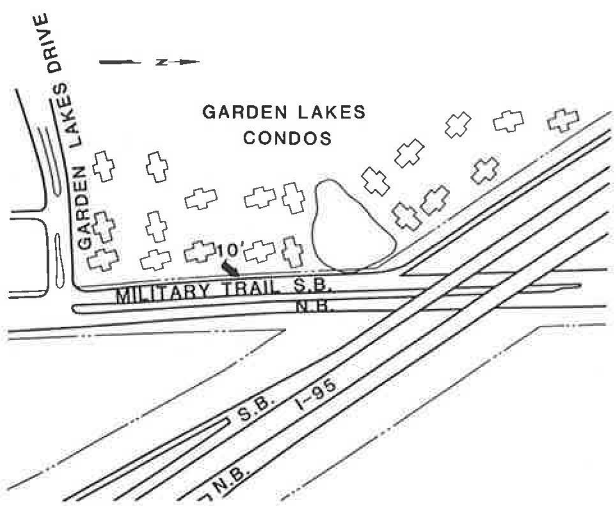

FIGURE 7 Garden Lakes condos after take.

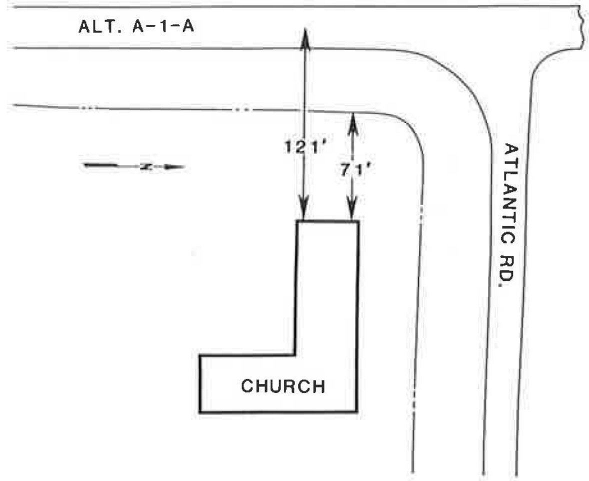

FIGURE 8 Gardens Baptist Church before take.

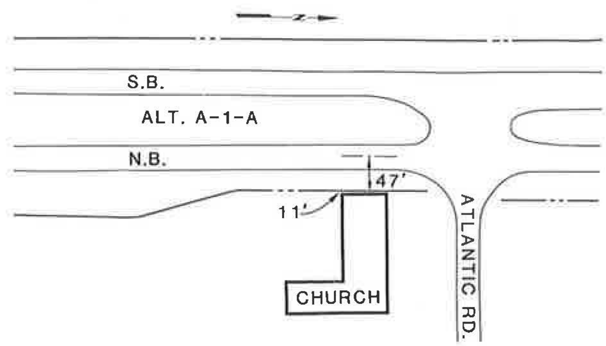

FIGURE 9 Gardens Baptist Church after take.

tion. The homeowners' contention was that noise would be a problem and abatement should be provided at the expense of the Department.

Several abatement alternatives were suggested for consideration, each of which exceeded $500,000 and, more importantly, would delay the final design and letting of a $17,000,000 project. To ensure that the noise issue was properly addressed and that the project schedule was maintained, it was suggested that the DOT attorneys contact the homeowners association about a possible award to allow the homeowners to design and build their own noise barrier on their own land.

This suggestion was met with approval by the homeowners association and on December 11, 1984, the DOT entered into a stipulated final judgment for the sum of $200,000. This amounted to $27,600 for the land taken and approximately $172,400 as cost to cure, notably to erect a noise barrier on the property of the homeowners association.

Department of Transportation v. Kenneth P. Thomas, et al.

Another case in Palm Beach County, State of Florida Department of Transportation v. Kenneth P. Thomas, et al. (1985), involved the Gardens Baptist Church of Palm Beach Gardens. The widening of Alternate A-1-A (State Road 811) from a two-lane to a four-lane roadway required the taking of approximately 19,000 ft^2 of church property. In the before setting (Figure 8), the main church building was located some 121 ft from the centerline of the highway. After construction, the centerline of the northbound roadway (closest to the front of the church) was 47 ft from the church (Figure 9).

The owners of the church believed that the adverse impact on the church resulting from traffic noise would not be tolerable unless the building was relocated on the eastern portion of the church property. This would put the church at a distance from the highway that was similar to that before construction. Excluding the value of the land taken for the project, the church requested $97,158 for cost to cure. This involved the physical relocation of the church building, a concrete-block structure.

The Department's attorney questioned the wisdom of this expenditure and requested a special noise study. The results of this investigation identified two mobile homes that were being used as classrooms for Sunday School and for a day school during the week. Although the adverse impact from noise on the church was determined to be minimal and did not warrant relocation of the church, the portable classrooms presented a totally different problem.

Two methods to relieve the noise problem were suggested in the noise study. One was to construct a noise barrier wall on the DOT right-of-way at an estimated cost of $52,000. The second alternative was to relocate the portable classrooms on the east side of the church and use the church building as a noise screen. This relocation was estimated to cost $5,000.

Before the trial, the attorneys for both parties met, along with the noise experts and the appraisers for both sides. Negotiations led to the conclusion that some remodeling of the church would enhance its utility and also reduce interior noise levels. This cost to cure was shown to be less than the estimated severance damages. The cure involved relocating the front entrance of the church, replacing single-paned windows with double-glazed windows, and relocating the two portable classrooms.

The stipulated final judgment, signed on January 4, 1985, awarded the church $73,245 for full payment for the property taken and for damages to the remainder. This breaks down to $19,660 for the land and $53,585 for damages, of which $34,385 was needed to cure the noise problems.

Department of Transportation v. Gideon Clack, et al.

The final case study to be reviewed also involved a church. In the State of Florida Department of Transportation v. Gideon Clack, et al. (1985), the DOT needed to acquire 175 ft^2 of land from St. Michael and All Angels Church. This Episcopal church, located in Tallahassee, was situated in a quiet residential area of the city (Figure 10). The realignment and extension of a pair of existing one-way streets resulted in the taking of a small corner of the subject property.

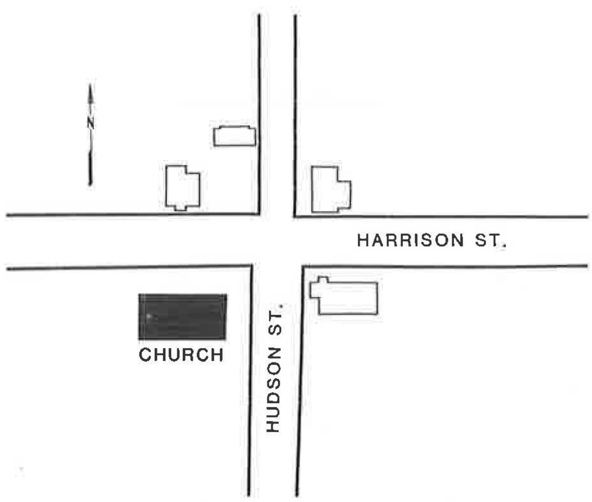

FIGURE 10 St. Michael and All Angels Church before take.

During the condemnation proceedings, the church contested the appraiser's valuation, which was set at $450. They claimed that the church was going to be a total loss because of the proximity to an arterial highway (Figure 11) and all the noise, traffic, and loss of on-street parking. The church sought $339,000 on the basis of the value of the property in the before setting.

A review of the environmental studies and the attendant noise study revealed that no significant noise impacts were expected. By using an indoor-outdoor noise loss comparison and assessing a second church in a similar setting located on the existing arterial one-way pair, the court determined that no loss of utility to the first church was anticipated.

The final judgment, signed on January 24, 1985, awarded the church $10,000 for the property taken and damages. This amounted to $450 for the value of the land and $9,550 for damages. Noise was not separated from other damages, but its contribution was considered negligible.

In both cases involving churches, the DOT staff attorneys were of the opinion that a jury trial would have been detrimental to the Department's position. This is based on experience and a knowledge of the importance of quiet in the church setting, accentuated by an emotional involvement. In his Recommendation of Settlement, one DOT attorney noted that "the moral to be gained is that in Leon County aesthetic-type issues such as destroying shrubbery, taking trees or churches, or running up against 'little old ladies,' are troublesome for a condemning authority" (6,p.3).

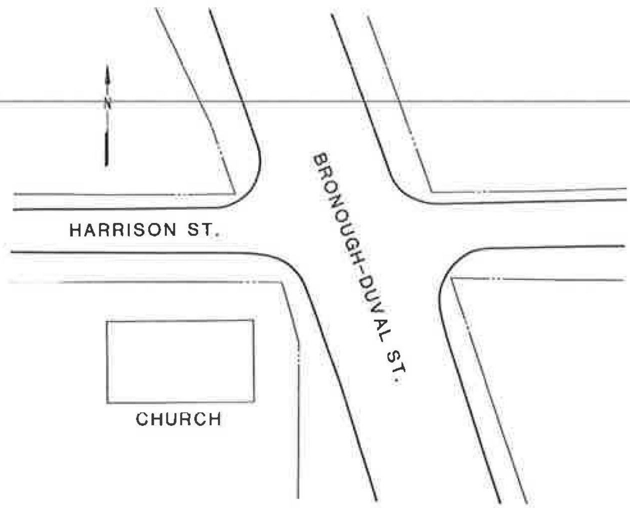

FIGURE 11 St. Michael and All Angels Church after take.

SUMMARY AND CONCLUSION

It is evident that Florida courts and attorneys involved in eminent domain proceedings have come to recognize noise as an item to be considered in the taking of property where there is a remainder. Although the courts have held that noise is not compensable unless the test of "severe" damage is met, it may be considered in severance damages. As each year passes, more and more highway projects will be facing noise as an issue in eminent domain proceedings.

This leads one to the conclusion that noise specialists must do a very thorough job of documenting existing and future noise conditions in their environmental review, especially for sensitive sites such as churches. In addition, attorneys and appraisers alike will need to address noise impacts as a possible damage issue and be prepared to deal with noise in a learned and professional manner.

ACKNOWLEDGMENTS

The contributions of many Florida Department of Transportation professionals that made this paper possible need to be recognized. Special recognition is due Ken Towcimak and Charles Stratton for their guidance and advice. To Jay Reilly and Jack Scruggs of the Eminent Domain legal staff goes a tip of the hat for the use of their files and their advice. Also a note of gratitude to the clerical staff of Eminent Domain for digging up old files and tolerating many interruptions. Finally, recognition is due Roger Eudy for excellence in the graphics.

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Publication of this paper sponsored by Committee on Transportation-Related Noise and Vibration.

Analyzing Construction Noise by a Level/Duration Weighted Population Technique

WILLIAM BOWLBY, ROSWELL A. HARRIS, and LOUIS F. COHN

ABSTRACT

A technique is described for comparing the potential noise impacts of construction hauling for a number of project alternatives. The technique is used on a modification of the level weighted population method to account for the duration of the hauling activity on the various haul route links; the resultant descriptor is termed Level/Duration Weighted Population (LDWP). A complex microcomputer spreadsheet was developed to facilitate data entry and calculation of LDWP for a base case and each study scenario, as well as a relative change in impact (RCI) over the base case for the scenarios.

River flood control construction projects funded by the U.S. Army Corps of Engineers require environmental assessments. Project alternatives typically include the construction of tall levees or flood walls or the cutting of channels to divert the river flow from floodplain. Such projects can take as long as 6 to 7 years to construct; hence, a serious potential impact of the project can be construction noise--in particular, the extensive material-hauling operations.

To assess and compare the construction haul-noise impacts of a set of different alternatives for a flood control project in Harlan, Kentucky, a technique was developed that considered existing community noise levels, future haul-noise levels, duration of haul activities, and population densities. In this paper that technique is described; it was implemented with a sophisticated microcomputer spreadsheet program.

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PROBLEM DEFINITION

Harlan, Kentucky, and its neighboring communities of Loyall, Rio Vista, and Baxter are located along the Cumberland River and two of its forks in Southeast Kentucky (1). The study area, shown in Figure 1, is characterized by steep-sided valleys with most of the commercial and residential development concentrated in narrow floodplains. Major floods occur mostly in the winter or spring; the flood of record, in April 1977, crested at over 30 ft above gauge zero. To minimize potential future damage, the Corps is evaluating a series of alternatives for flood control (1). These alternatives include the following:

1. A-77: Building levees and flood walls in the Harlan and Loyall areas for the 1977 flood levels.
2. A-SPF: Same as A-77, but for the Standard Projected Flood level.
3. B-SPF-Filled: Cutting new channels through the 200- to 300-ft high hills behind Harlan and Loyall, building diversion dikes along the river at the ends of these channels, and filling in the existing riverbeds between the diversion dikes.
4. B-SPF-Unfilled: Same as B-SPF-Filled, but leaving the riverbeds unfilled in the diversion areas.

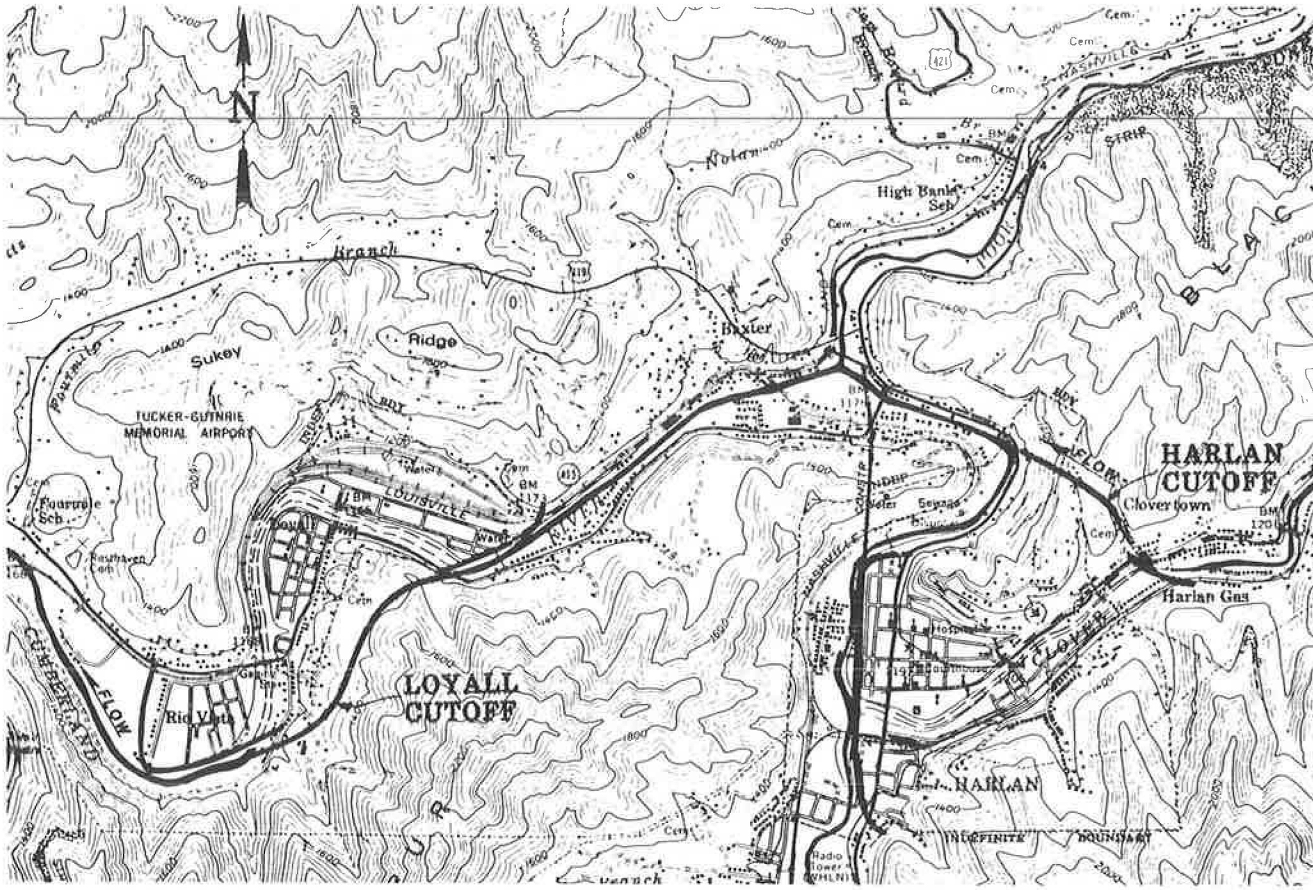

FIGURE 1 Project area, Harlan County, Kentucky.

5. C-SPF-Filled: A combination of A-SPF in the Harlan area (new channel) and B-SPF-Filled in the Loyall area (flood walls and levees).

6. C-SPF-Unfilled: The same as C-SPF-Filled, but leaving the riverbed in Harlan unfilled.

Early in its alternatives analysis process, the Corps identified several potential short- and long-term noise impacts that warranted additional investigation. The major long-term impact dealt with traffic noise, namely,

1. A potential increase in levels in Harlan because of reflections off flood walls and
2. A potential decrease in levels in Loyall because of relocation of State Route 840 along a bench cut in the Loyall channel.

Secondary long-term impacts dealt with railroad noise, namely,

1. A potential increase in levels because of reflections off the flood walls in north Loyall and south Harlan and
2. A potential decrease in levels because of shielding by the flood walls in western Loyall.

The major potential short-term noise impact, as defined by the Corps, dealt with construction. Although there would be many sources of noise during construction, the scope of services for the project noted that the only source to be analyzed quantitatively was the truck hauling. One should note that in this case the qualifier "short-term" implies a 4- to 7-year duration, depending on the chosen alternative. The impact analysis technique described in this paper will be limited to the haul-noise impact assessment strategies.

CRITERIA AND MODELS

A major consideration in the analysis was that much of the hauling would be on the existing road network. As a result, the existing noise environment for the potentially affected residences was established largely by highway traffic. The assessment technique thus needed to accommodate impact criteria and prediction methods for construction haul trucks as well as for conventional highway traffic.

Time-Averaging Concept

Accepted criteria for transportation and construction noise impacts deal with the "time averaging" of the acoustic energy reaching a sensitive receptor. The averaging is done over different time periods depending on the noise source. The time-averaged level, or A-weighted equivalent sound level, is commonly abbreviated L_{eq}, with units of decibels (dBA). The A-weighting refers to an attenuation or amplification of the sound pressure levels of the different frequencies composing environmental noise to simulate human hearing response.

Traffic Noise Criteria

For traffic noise, FHWA requires state highway agencies to use the hourly time-averaged level [L_{eq}(1h) or $L_{eq}(h)$] or the hourly 10th-percentile exceedance level [$L_{10}(h)$] (2). Traffic noise predictions are done for the "worst" noise hour, which typically occurs during the daytime, inclusive of the morning and evening rush periods.

The FHWA noise standards (2) indicate that noise mitigation must be considered when (a) the future "design-year" project levels "substantially exceed" existing levels and (b) the future levels "approach or exceed" stated noise abatement criteria. For residential land use, the criterion is an $L_{eq}(1h)$ of 67 dBA. Note that these criteria define when mitigation must be considered, not when an impact occurs. Although not stated in the noise standards, subsequent FHWA policy guidance suggests that impacts occur when the $L_{eq}(1h)$ exceeds 55 dBA (3). The standards also do not define the phrase "substantially exceed," although many agencies have settled on an increase of 10 to 15 dBA as an indication of impacts worthy of mitigation study.

Construction Noise Criteria

For construction noise, the U.S. Army Construction Engineering Research Laboratory (CERL) supports use of a measure called the representative level ($\overline{L_A}$) (4). $\overline{L_A}$ is defined by a Society of Automotive Engineers (SAE) measurement procedure, which was developed before the common availability of integrating sound-level meters (5), as follows:

$$\overline{L_A} = \sum_{I=1}^{n} (L_A)_i/n \qquad (1)$$

where $(L_A)_i$ are those sound-level samples that fall within a range from the maximum sampled level to 6 dB less than the maximum sampled level [e.g., if the maximum sampled level was 70 dB, all sound-level samples from 64 to 70 dB would be $(L_A)_i$ values] and n is the number of $(L_A)_i$ values used for computing the arithmetic average.

$\overline{L_A}$ is related to the time-averaged level (L_{eq}) by the fraction of samples within 6 dB of the highest:

$$L_{eq} = \overline{L_A} - \Delta \qquad (2)$$

where

Δ = 0 dB for $0.8 < (n/60) \leq 1.0$,
= 1 dB for $0.7 < (n/60) \leq 0.8$,
= 2 dB for $0.6 < (n/60) \leq 0.7$,
= 3 dB for $0.5 < (n/60) \leq 0.6$,
= 4 dB for $0.4 < (n/60) \leq 0.5$,
= 5 dB for $0.3 < (n/60) \leq 0.4$,
= 7 dB for $0.2 < (n/60) \leq 0.3$, and
= 10 dB for $0 < (n/60) \leq 0.2$.

The CERL specifications do not specify a particular period over which levels should be averaged, although use of the SAE procedure will typically require at least 30 min of data collection. CERL simply specifies daytime and nighttime periods.

In addition, the CERL impact criteria specifications address noise generated within the construction boundary; they do not address trucks hauling beyond the site (4). Nor does the FHWA have construction noise impact criteria; as guidance, it suggests that users could develop their own criteria by considering absolute levels as well as relative differences in levels (6).

The FHWA noise standards address construction noise but do not require prediction of construction noise levels for federal-aid highway projects (2). However, FHWA models are available that predict 1-hr or 8-hr time-averaged levels [$L_{eq}(1h)$ or $L_{eq}(8h)$] (7,8). One component noise source in the FHWA construction noise model is the haul truck. The model requires specification of an hourly flow rate (trucks per hour), thus assuming a constant flow throughout the day. As a result, the predicted hourly L_{eq} will be equal to the 8-hr average. Because haul-truck noise generation is so similar to normal highway truck noise generation and because the haul trucks will often travel the same paths as does the normal traffic, the most appropriate measure for studying haul-truck noise for this project was the hourly L_{eq} or $L_{eq}(1h)$.

Relative Change in Impact

Because this study needed to gauge the impact of the introduction of the construction haul traffic to a static situation, it was appropriate to use some method of comparing "build" and "no-build" levels. Such a method was described by Kugler et al. in 1976 (6). The method is based on the concept of the level-weighted population (LWP), also referred to as "fractional impact." The method uses the "day-night" time-averaged level, or L_{dn}, which is a 24-hr average of acoustic energy where 10 dB is added to all values between 10:00 p.m. and 7:00 a.m. as a penalty for nighttime sensitivity.

A scale is established where an L_{dn} of 55 dB is assumed to "highly annoy" zero percent of the population, whereas an L_{dn} of 75 dB is assumed to highly annoy 100 percent of the population. The number of people exposed to different L_{dn} values for each case is then weighted according to the L_{dn} values. An "equivalent highly annoyed" population (or level-weighted population) is then computed for the base case and the alternative being studied. Mathematically,

$$LWP = \sum_{i=1}^{n} 0.05P_i \left[(L_{dn})_i - 55\right] \qquad (3)$$

where P_i is the number of people exposed to day-night level $(L_{dn})_i$ and n is the number of L_{dn} values or ranges used in the calculations typically; the calculation is performed by grouping subjects in 5-dB L_{dn} bands.

A relative change in impact (RCI) is then computed by subtracting the LWP for the base case (LWP_{base}) from the LWP for the alternative (LWP_{alt}), dividing by the base-case LWP, and multiplying by 100:

$$RCI = \left[(LWP_{alt} - LWP_{base})/LWP_{base}\right] \times 100 \qquad (4)$$

The LWP values for each case are also good indicators of the absolute impact as compared with an L_{dn} of 55 dB. The RCI method has been used for nontraffic noise sources as well, as illustrated in the U.S. Environmental Protection Agency background document on rail carrier noise standards (9).

For the flood control study, it appeared that a slightly modified version of the RCI method was the most appropriate to compare the various construction haul scenarios for each project alternative. Instead of using a 24-hr L_{dn}, which is appropriate railroad noise, the hourly L_{eq} was used. Kugler et al., as well as the EPA, suggested that an L_{dn} of 55 dB was an indicator of zero percent highly annoyed. As noted earlier, FHWA considers a traffic noise L_{eq} (1h) of 55 dB to also represent no impact. Given the similarity of haul-truck noise to traffic noise, the construction noise LWP values could also be computed by using a 55-dB L_{eq} (1h) as the baseline value. The LWP for the various construction haul scenarios could then be compared with a base-case LWP, which would be caused by traffic noise with no project haul trucks. Thus, the relative impacts of each haul scenario could be analyzed by computation of the RCI.

Traffic Noise Model

Once this means of quantifying and comparing impacts had been selected, the next step was to choose models to predict future noise levels for traffic and construction haul trucks.

The accepted model for traffic noise is the FHWA Highway Traffic Noise Prediction Model (10), which consists of the basic acoustics equations for sound emission and propagation and attenuation by barriers. Several methods are available for using the model, including charts, nomographs, and various levels of computer programs. The nomograph method was the most appropriate for predicting base-case traffic noise levels given the general nature of the site modeling.

Several methods are available to predict haul-truck noise, including the FHWA HICNOM computer program (8) and the FHWA Highway Traffic Noise Prediction Model (10). The methods are similar in concept for the truck noise source, differing in the values for the basic emission-level equation. On the basis of observations by the study team during field sound-level measurements, the trucks currently in use in the project area for hauling coal have emission levels similar to the typical heavy truck modeled in the FHWA traffic noise model. These coal haul trucks, including muffler systems, are relatively new and generally well maintained. It was anticipated that many of these same, or similar, trucks would be employed for hauling during the flood control project construction. Therefore, it was appropriate to model them by using the heavy-truck vehicle type in the FHWA traffic noise model and use that model to predict hourly haul-truck L_{eq}-values.

STUDY METHOD

The study method consisted of a series of steps. First, the LWP technique needed to be modified to incorporate the duration of construction hauling in a particular area. This modification was a key factor in the analysis technique. Next, a haul network and haul scenarios were developed for each project alternative. Then, base-case impacts were determined as a basis for comparison with hauling impacts. Finally, the hauling impacts were determined and used to compute changes in impact relative to the base case. These steps are discussed in detail in the following paragraphs.

Consideration of Haul Duration

As noted earlier, the RCI technique is based on the fractional impact or LWP concept, which, in its simplest form, states that the impact on a few people exposed to high noise levels is equivalent to the impact on a larger number of people exposed to lower noise levels. In this technique, a person exposed to a level of 55 dB or less is assumed to receive zero impact, whereas a person exposed to a level of 75 dB is assumed to receive 100 percent impact. A linear change in impact is then applied for those exposed to levels between 55 and 75 dB; for example, a person would be considered 25 percent impacted at a level of 60 dB, 50 percent impacted at a level of 65 dB, and 75 percent impacted at a level of 70 dB.

The technique then involves the weighting of the population according to the noise-level exposures to determine an equivalent population that is 100 percent impacted. This normalization procedure thus gives a meaningful method to compare the relative differences between scenarios and hence alternatives.

Construction noise analysis has an additional factor that needed to be considered. Traffic noise, which forms the base case or "do-nothing" alternative, is typically considered a permanent type of noise. However, construction is a temporary noise of finite duration. The analysis technique thus needed to account for the duration of the haul activities. For example, it is obvious that a person exposed to noise from 100 haul trucks per hour for 2 years would be more seriously impacted than a person exposed to the same number of trucks for a 1-year period. The question is how to quantitatively compare the impact of the two situations.

Guidance may be found in the CERL report on construction noise specifications (4), in which a logarithmic relationship is used when durations are considered in its "maximum permissible" noise-level specification, normalized to a 32-day period. Specifically, each halving of the duration of the activity would raise the permissible noise level by 3 dB. Mathematically,

$$\Delta_{duration} = 10 \log (duration/32) \quad (5)$$

Choice of the 32-day period by CERL was arbitrary, probably a compromise on a 1-month's duration and a factor of 2 for ease of calculation. Thus, just as the dwelling units are normalized to an equivalent population that was 100 percent impacted, the haul operations of varying durations may be normalized to some base-case value. In this manner, one may redefine the LWP as a level/duration weighted population, or LDWP.

During project discussions, it was determined that the longest construction period for any of the alternatives would be approximately 7 years. It was decided therefore to normalize the levels to this period. Based on an assumption of 45 work weeks per year, a 7-year period equaled 315 weeks. Thus, the construction haul noise levels were adjusted for the LDWP calculation by

$$\Delta_{duration} = 10 \log (duration/315) \quad (6)$$

Representative Distance Bands

In performing the fractional impact analysis, one could predict a precise noise level at every house along a project haul-road link. However, given the nature of the analysis, such precision would be unwarranted and probably deceiving. A much more efficient method, with little loss in overall accuracy, would be to group the dwelling units on the basis of their distances from the haul link.

To accomplish this grouping, representative distance bands needed to be defined. Typical distances for traffic noise predictions are 25, 50, 100, 200, and 400 ft. Based on sound-level propagation calculations, five distance bands were defined: 10 to 35 ft, 35 to 70 ft, 70 to 165 ft, 165 to 280 ft, and 280 to 560 ft. The band outer limits are such that for soft-site propagation (grassy ground cover) the level at a house located anywhere within a given band would be within 2.2 dB of the level at the corresponding representative distance.

Noise levels could then be computed at the five representative distances, and those levels applied to all the houses within the corresponding distance bands. Thus, knowing the noise levels, adjusted for duration of activity, and the number of people exposed to those duration-corrected levels, one could compute an LDWP for a hauling scenario for a project alternative.

Development of a Hauling Network and Hauling Scenarios

Field reviews and project team meetings led to the definition of a series of links along existing roads or along construction roads that defined a potential network over which the haul trucks could travel. Figure 2 shows the link map on which a link is defined as a section of road connecting two numbered roads.

Then, for each project alternative (A-77, A-SPF, B-SPF-Filled, B-SPF-Unfilled, C-SPF-Filled, and C-SPF-Unfilled), quantities were established of the amounts of material to be removed from a channel cut or to be used to build a diversion structure or fill a riverbed. Next, on the basis of construction sequencing analyses, several scenarios were developed to accomplish the various haul activities, including hauling material from the Harlan or Loyall cuts to several potential disposal sites, hauling from several potential borrow areas to build the levees and diversion structures, and hauling material to fill the old riverbeds. Haul routes over particular links in the network were established for each scenario, and hourly haul-truck rates and weekly durations for the hauling activity were computed for each pertinent link.

Base-Case LDWP

The next step in the analysis involved determining a base-case impact on the dwelling units in the vicinity of the haul-road links due to traffic noise during the construction period.

The base-case traffic noise levels were computed for each distance for each link by using 1989 traffic data adjusted from 1982 data provided by the Kentucky DOT. Standard FHWA model equations for hourly L_{eq} prediction on soft sites were used for automobiles, medium trucks, and heavy trucks, as follows:

$$\left[L_{eq}(h)_i\right]_j = \left[(\overline{L_o})_E\right]_i + 10\log(N_i D_o/S) + 15\log(D_o/D_j) - 33.4 \qquad (7)$$

where

$\left[(\overline{L_o})_E\right]_i$ = 38.1 log(S) − 2.4 for i = automobiles,
= 33.9 log(S) + 16.4 for i = medium trucks,
= 24.6 log(S) + 38.5 for i = heavy trucks,

S = vehicle speed (mph),
N_i = hourly flow rate of the ith vehicle type,
D_o = reference distance of 50 ft,
D_j = perpendicular distance from the road to the receiver (ft), and
33.4 = constant adjusting for unit conversion and infinitely long soft-site propagation.

Levels were calculated for values of D_j of 25, 50,

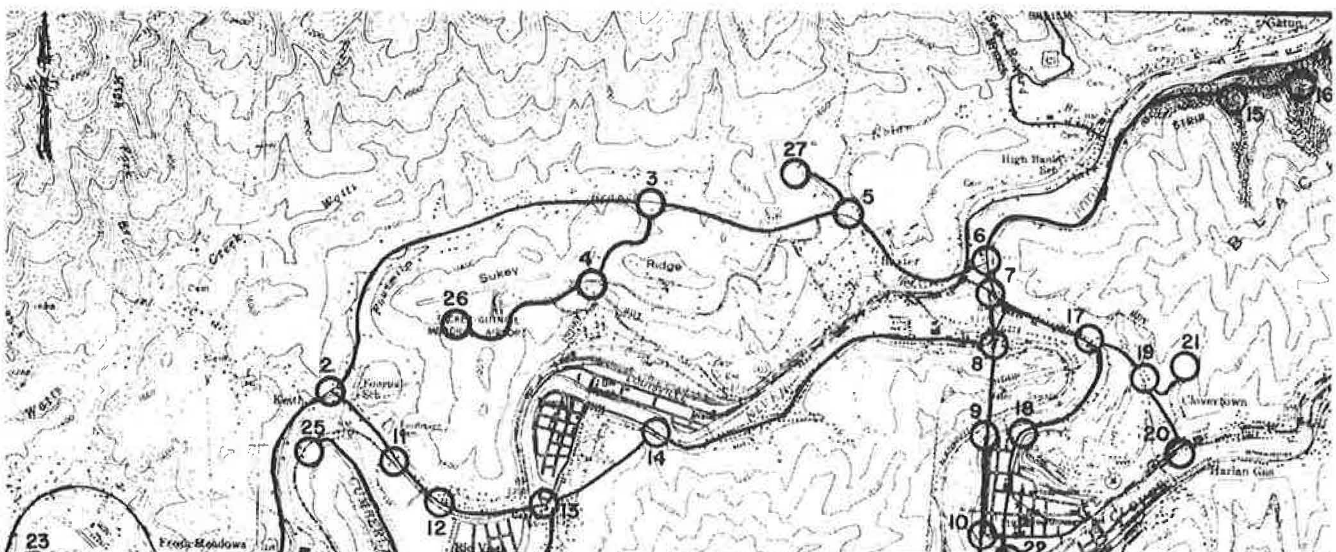

FIGURE 2 Construction haul route link network.

100, 200, and 400 ft. Then, the $[L_{eq}(h)_i]$ values were combined for the total hourly average sound level on the link at each distance $[L_{eq}(h)_T]$:

$$\left[L_{eq}(h)_T\right]_j = 10 \log \left\{\sum_i 10^{\left[L_{eq}(h)_i\right]_j/10}\right\} \quad (8)$$

For several of the potential haul links, no future highway traffic data were available, or no road actually existed. In these situations, the base-case noise levels were determined from field measurements of existing noise levels.

A base-case LDWP was then computed for each of the five distance bands for each link, $(LDWP_{BASE})_j$, based on the predicted traffic noise levels and number of dwelling units within each band:

$$(LDWP_{BASE})_j = 0 \quad \text{if } \left[L_{eq}(h)_T\right]_j \leq 55 \text{ dB}$$
$$= 0.05P_j\left\{\left[L_{eq}(h)_T\right]_j - 55\right\} \quad \text{if } \left[L_{eq}(h)_T\right]_j > 55 \text{ dB} \quad (9)$$

where P_j is the number of dwelling units in the jth band for this link.

The base-case LDWP values for each distance band for a link were then arithmetically summed to get a base-case LDWP for the link. The LDWP values for each link were then summed to get a total base-case LDWP $(LDPW_{BASE})$. This total was then used as a basis for comparison for all of the haul scenarios for each project alternative.

Construction Haul Scenario LDWP

The next step was to determine the construction LDWP $(LDWP_{CONSTR})$ for the given haul scenario under study for a given project alternative. This calculation first involved computation of an average sound level at each representative distance for the construction haul traffic, $[L_{eq}(h)_{haul}]_j$, on each link for that scenario, using the heavy-truck emission level in Equation 7. Then, the overall hourly average sound level at each representative distance, $[L_{eq} \cdot (h)_{const}]_j$, was determined by a logarithmic combination of the base-case average sound level, $[L_{eq} \cdot (h)_T]_j$, and the duration-adjusted haul traffic average sound level, $[L_{eq}(h)_{haul}]_j$, in a similar manner to that shown in Equation 8. Finally, the LDWP for each distance for that link was determined in a similar manner to that in Equation 9 by using these overall noise levels.

These distance-related LDWP values were then summed to get a total LDWP for the link. If a link had no construction traffic for a particular scenario, the construction scenario LDWP for that link would be equal to the base-case traffic LDWP. The total LDWP for the haul scenario $(LDWP_{CONST})$ was then determined by arithmetically summing the LDWP value for each link in the project network.

RCI

The RCI for each scenario was then determined by

$$RCI = \left[(LDWP_{CONSTR} - LDWP_{BASE})/LDWP_{BASE}\right] \times 100 \quad (10)$$

Once RCI values were determined for each scenario for a given project alternative, a worst-case scenario could be defined for that alternative, and a worst-case RCI computed. Thus, the potential construction haul-noise impacts of each alternative could be compared as part of the overall study of the flood control project alternatives.

USE OF A MICROCOMPUTER SPREADSHEET

To perform the analysis, a VisiCalc spreadsheet template was developed (VisiCalc is a registered trademark of VisiCorp). The spreadsheet concept was used in part because of its convenience for data entry and formatted output. The analysis called for a good deal of data entry. For example, the analysis network had over 30 construction and traffic links; for each scenario to be analyzed, the pertinent links had construction truck volumes and durations. Each link had base-case noise levels and numbers of dwelling units for each of the five representative distance bands. This extensive arrayed data entry was greatly simplified by the screen-editing feature of a spreadsheet. In addition, as over 40 individual scenarios needed to be analyzed for the project alternatives, a spreadsheet offered an efficient means for producing concise, readable output. VisiCalc was chosen because of its availability to the authors and their familiarity with it.

Six similar templates were established, one for each project alternative. Each template had data common to all of the alternatives as well as data unique to each. The basic template consisted of four sections, which are described in more detail in the succeeding paragraphs:

1. A data base of the construction haul-truck volumes, travel speed, and durations of hauling along each link for all of the scenarios for a given alternative; this section was unique for each alternative.
2. A data base of a number of dwelling units and base-case traffic noise levels for each distance band for each link; this section was the same for each alternative.
3. A look-up table, common to all alternatives, of haul-truck reference emission levels as a function of travel speed.
4. A calculation area for the construction haul sound levels, the LDWP for each link, and the overall LDWP and RCI for the scenario; this area was utilized for each scenario for each alternative.

Figure 3 shows a portion of Section 1 of the spreadsheet for the B-SPF-Filled alternative. Note that link names (LINK) consist of the node numbers at both ends of a link and that the links were segregated by geographic location (AREA). The speeds along each link (SPEED) were assumed to be the same for all scenarios and alternatives, although these data would be easily changed variables. The rest of the columns of this section of the template are for entry of haul traffic hourly flow rates (VOL) and activity durations in weeks (DUR) for each scenario or case to be studied for each alternative. The VOL and DUR values were developed externally for the appropriate links on the basis of data on the amount of material to be moved, location of borrow or disposal sites, and construction sequencing. These values were then simply entered into the corresponding cells of the spreadsheet template for that alternative.

Figure 4 gives a portion of Section 2 of the spreadsheet. The data in this section remained the same for all of the alternatives. On the left, again, links are identified by node numbers. In the center, the number of dwelling units is listed by distance band; these data were collected from maps and field reviews. To the right are the base-case daytime hourly traffic noise levels for the analysis year 1989 as a function of distance from the link. These data were either externally computed by using the FHWA model nomograph or assumed based on the existing noise level field survey. (The data could

U.S. CORPS OF ENGINEERS
HARLAN FLOOD CONTROL NOISE STUDY
CONSTRUCTION HAUL NOISE ANALYSIS

ALTERNATIVE: BSPF FC

CASE 1: HARLAN CUT, NO BACK HAUL
CASE 2: FHC-L/119, FLC-L/B-RIO, ROCK TO A/P
CASE 3: FHC-L/119, FLC-L/B-RIO, ROCK TO A/P-L
CASE 4: CASE 1 PLUS 3

	CASE:		1	1	2	2	3	3	4	4	5	5
AREA	LINK	SPEED	VOL	DUR	VOL	DUR	VOL	DUR	VOL	DUR	VOL	DUR
DAYH	1-23	30										
	1-29	20					64	79	64	79		
	29-24	40					64	79	64	79		
	1-2	50					64	79	64	79		
RIO	2-11	40			64	192	64	182	64	182		
	11-12	40			68	192	68	182	68	182		
	12-13	30			64	192	64	182	64	182		
	13-25	20										

FIGURE 3 Section of spreadsheet template: haul speeds, volumes, and durations for each case for an alternative.

		NO. OF DWELLING UNITS BY DISTANCE BAND FROM ROAD					BASE CASE TRAFFIC NOISE LEVELS, 1989 (LEQH, DBA)				
AREA	LINK	25	50	100	200	400	25	50	100	200	400
DAYH	1-23	2	6	1	0	4	50	50	50	50	50
	1-29	7	2	2	4	3	60	57	52	48	43
	29-24	0	7	8	2	2	60	57	52	48	43
	1-2	1	3	0	2	0	77	74	70	65	61
RIO	2-11	0	2	4	1	2	69	66	62	57	53
	11-12	1	4	12	3	5	69	66	62	57	53
	12-13	1	7	25	24	52	67	64	60	55	51
	13-25	2	20	15	4	34	53	53	53	53	53

FIGURE 4 Section of spreadsheet template: dwelling units and base-case traffic noise levels.

have been computed by using the spreadsheet concept, but project scheduling restricted development time.) Along links where traffic was the clearly responsible major noise source, the levels show a 3-dB reduction from 25 to 50 ft, representing hard-site propagation, whereas a 4.5-dB reduction per doubling of distance beyond 50 ft was exhibited, representing soft-site propagation. All of the data in this section of the template would be referenced by the formulas in Section 4 of the template.

Shown in Figure 5 is Section 3 of the spreadsheet, a simple look-up table of heavy-truck reference energy and mean emission level as a function of speed. Note that at speeds below 30 mph, a level of 83 dB was assumed to represent slightly increased levels due to acceleration and deceleration noise. During the calculations in Section 4 of the template, the appropriate speed-dependent emission level would be read from this table. The look-up function was used rather than the emission-level equation for reasons related to calculation speed and ease of programming.

REF. LEVELS	
SPD	LEV
20	83
25	83
30	80
35	82
40	83
45	84
50	85
55	86

FIGURE 5 Section 3 of spreadsheet template: truck reference emission levels.

Figure 6 shows a portion of the heart of the spreadsheet--the calculations. Shown in the upper left section is the number of the case (or scenario) being studied for a particular alternative. In this example, it is case 3 of the B-SPF-Filled alternative. The case number is a key that is used in this section of the spreadsheet to read the appropriate data from the other three sections. Once Sections 2 and 3 had been prepared for all of the alternatives and Section 1 prepared for all of the cases for a given alternative, all that had to be done to perform the calculations for a given case was to enter

BSPF FC
CASE: 3 ALPHA = .5
REFERENCE DURATION = 315
CRITERION LEVEL = 55

AREA	LINK	SPEED	VOL	DUR	REF LEV	LEVEL AT DISTANCE: 25	50	100	200	400	LEVEL/DURATION WEIGHTED POPULATION 25	50	100	200	400	SUM
DAYH	1-23	30	0	0	80	0	0	0	0	0	0	0	0	0	0	0
	1-29	20	64	79	83	76	73	68	64	59	5	1	1	1	0	8
	29-24	40	64	79	83	73	70	65	61	56	0	3	2	0	0	5
	1-2	50	64	79	85	74	71	67	62	58	1	3	0	1	0	5
RIO	2-11	40	64	192	83	73	70	65	61	56	0	1	2	0	0	3
	11-12	40	68	192	83	73	70	66	61	56	1	3	6	1	0	11
	12-13	30	64	192	80	71	68	63	59	54	1	5	11	5	0	22
	13-25	20	0	0	83	0	0	0	0	0	0	0	0	0	0	0
HAR	10-22	20	0	0	83	0	0	0	0	0	0	0	0	0	0	0
	20-22F	20	0	0	83	0	0	0	0	0	0	0	0	0	0	0
	10-28	20	0	0	83	0	0	0	0	0	0	0	0	0	0	0
	22-28	20	0	0	83	0	0	0	0	0	1	1	1	0	0	3
															SUM =	269

LDWP FOR CASE # 3 = 269
LDWP FOR BASE CASE = 238
RELATIVE CHANGE IN IMPACT = 12.90

FIGURE 6 Section 4 of spreadsheet template: calculation of construction haul levels, LDWP, and RCI.

the corresponding case number in Section 4. When the calculations were completed, this section of the spreadsheet could be quickly printed and the next case number entered to have the next set of calculations performed.

Shown on the left of Figure 6 are the link names, again in terms of node numbers. The next three columns represent the haul speed, volume, and duration for the case being studied. These data are read directly from Section 1 of the spreadsheet according to the case number entered, as described earlier. The next column, REF LEV, is the truck emission level, read from Section 3 of the spreadsheet, based on the speed value, which had been read from Section 1. These data look-up features eliminated one source of update anomalies that can plague data bases. If one wanted, for example, to change the travel speed along a certain link, the change would only have to be made once, in Section 1, and the change would automatically be incorporated into Section 4.

The next five columns (LEVEL AT DISTANCE) represent the construction haul traffic hourly L_{eq} for this link as a function of distance, based on Equation 7 for heavy-truck emission levels. The calculation was set up for soft-site propagation beyond 50 ft, although this could easily be changed by modifying the ALPHA = .5 cell of the spreadsheet, shown above the column heading. A typical formula in one of these haul L_{eq} calculation cells is as follows:

```
@IF (F140=0, 0, +H140+(10+@LOG10(F140*50/E140))
        +(10*(1+K136)*@LOG10(50/J138))
        - 33.4).
```

This formula says that if the haul volume, VOL (located for this link in the cell at column F, row 140), is zero, assign a value of zero for the level, or else compute the level by adding the reference level, REF LEV (in cell H140), to the flow adjustment--10log(VOL*50/SPEED)--and to the distance adjustment--10(1+ALPHA)log(50/DISTANCE)--and subtracting a constant value, 33.4.

Shown on the right-hand side of Figure 6 are the LDWP calculation results for each distance, and to the extreme right, the LDWP sum for all distances for each link. The calculation that occurs in each of the individual distance cells is complex. A typical cell formula is

```
@IF (G74 = 0, 0,
   @IF(G140=0, 0.05*G74*@MAX(0, L74-A6),
   0.05*G74*@MAX(0, (A3*@LN(X74+@EXP(J140
   +(A3*@LN(G140/A5)))*A4))-A6)))).
```

This formula states that if the number of dwelling units for this link (in cell G74) is zero, set LDWP to zero, or else do the following:

1. If the construction duration, DUR (G140), is zero, compute the LDWP as 0.05 times the dwelling units (G74) times the maximum of zero or the difference between the traffic L_{eq} (L74) and the criterion level (A6);
2. Or else compute the LDWP as follows:
   a. Adjust the construction level (J140) by the logarithmic ratio of the duration (G140) to the reference duration (A5);
   b. Logarithmically combine this adjusted level and the base-case traffic noise level to get the overall level;
   c. Subtract the criterion level (A6) from the overall level; and
   d. Compute the LDWP by multiplying this difference by the number of dwelling units (G74) times 0.05.

This calculation is performed for each distance for each link. These distance-based LDWP values are then summed for each link in the rightmost column of the spreadsheet and then summed over all of the links to get the total LDWP for this case for this alternative (shown as 269 in the bottom right of Figure 6). Finally, the RCI for this case is computed, as shown in the lower left of the figure. In this example, this particular hauling scenario (Case 3) for alternative B-SPF-Filled will cause a 12.9 percent increase in the LDWP over the base case of 1989 traffic.

Again, once Sections 1-3 were prepared, all that had to be done to compute the RCI for a given case for a given alternative was to change the case number at the top of Section 4. In this manner, the many cases could be quickly analyzed and the results compiled and evaluated.

SUMMARY AND CONCLUSIONS

To assist the Corps of Engineers in assessing the construction haul-noise impact of a series of flood control project alternatives, a technique was developed based on a modification to the LWP technique to account for construction haul activity duration. The resulting parameter was the LDWP.

By computing an LDWP for a base case of no construction hauling, where the major noise source was generally traffic, and computing an LDWP for the duration-adjusted construction haul-noise levels combined with the regular traffic noise levels, the relative change in impact (RCI) could be determined for different haul scenarios for each proposed alternative. The analysis technique produced aggregate impact values for comparing alternatives as well as disaggregate details on the link-by-link impacts that could be used subsequently in mitigation strategy development.

The technique was implemented with a complex microcomputer spreadsheet template that permitted easy data entry, rapid calculation of impacts, and immediate formatted presentation of results. The spreadsheet included several sections of data for each project alternative that were accessed by the calculations section by using look-up type functions. Development of the spreadsheet template was somewhat time-consuming and not very amenable to easy modification of the template structure. However, use of the template, once developed, was simple and fast, and permitted many different scenarios to be easily analyzed.

The analysis procedure, then, involved setting up the first section of each template for each alternative and running the calculations in the last section of the template for each case for each alternative. The resultant spreadsheets were printed after each recalculation. The RCI values were then tabulated for all of the cases for each alternative, permitting an evaluation of the relative impacts as input into the environmental assessment.

ACKNOWLEDGMENTS

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Noise Emission Levels for Vehicles in Ontario

F. W. JUNG, C. T. BLANEY, and A. L. KAZAKOV

ABSTRACT

The FHWA traffic noise prediction model (STAMINA) has been adopted in Ontario because of its flexibility and analytical features, which accommodate changed conditions through simple updating procedures. Major inputs for STAMINA are the reference energy mean emission levels of vehicle classes as a function of speed. These functions were established by the FHWA in their original report on the basis of data collected in the United States before 1978. However, conditions in Ontario in 1985 are different, and the noise emission level functions used in the STAMINA and other related programs should be reevaluated. Data on reference emission levels of cars and of medium and heavy trucks were collected during 1984 and 1985, processed, and statistically analyzed. From these data, functions of reference noise emission levels with vehicle speed were established for those vehicle groups. These functions can be used in programs derived from the FHWA model. The findings in Ontario confirm those in other jurisdictions in the United States, namely, that heavy trucks emit less noise at high speeds than originally indicated by the FHWA model. Further, it is shown that about 4 percent of heavy trucks are notoriously noisy compared with the general population and cause an upward shift of the reference emission level function by 0.5 to 1 dBA. These noisy trucks are relatively rare events, which may or may not be missed in noise measurements of short duration (20 min), but they have a high impact on the level of noise pollution.

Numerous methods have been developed to estimate or predict highway traffic noise, a major source of noise pollution in residential areas. In Ontario for many years the standard method of predicting traffic noise adjacent to freeways and highways was that developed by Hajek (1). However, his model was empirically based on numerous field measurements and comprises a mathematical simulation of overall traffic flow noise. Thus, like other empirical models, this method was bound to become outdated as soon as real-world conditions changed. For example, more stringent vehicle emission level standards would reduce noise effectively and invalidate some of the assumptions on which the model was based. Reformulation of such empirical models is rather difficult because one must resort to repetition of numerous field measurements.

In 1977 FHWA developed an analytical model for traffic noise prediction based on and built up from basic principles of acoustics (2). Such a model can easily be calibrated for new conditions because reference noise emission levels from various classes of vehicles are used as separate independent inputs. Once mean values of these levels have been established, the total noise from overall traffic flow is then calculated from the amount and composition of traffic as it exists or is projected for a particular highway. When the FHWA model was published, certain reference noise emission levels were recommended and spelled out as functions of speed and vehicle type (3). At the same time, however, it was recommended that each agency (state or province) carry out its own investigations of noise emission levels of the prevailing classes of vehicles, taking into account regional conditions such as composition and design of truck or automobile populations, enforcement, and compliance with regulations and standards. Furthermore, such conditions may change significantly in the course of time, so that collection and processing of vehicle noise data should be repeated periodically (i.e., every 5 or 10 years).

In other words, once sufficient emission level data have been collected, the analytical character of the FHWA model allows for a relatively simple update of prediction calculations, as described and reported in the following discussion.

In 1984 the state of Georgia reported (4), on the basis of a relatively small sample of measurements, that heavy and medium trucks were emitting less noise at higher speeds than that predicted by the FHWA model (1,2,5). In other words, the FHWA model was overestimating noise levels for traveling near the legal speed limit (80 to 100 km/hr).

In 1985 a California report (6) based on a much larger sample of measurements showed similar findings--trucks at higher speeds are less noisy.

The analytical traffic noise prediction model of the FHWA was introduced in Ontario in 1982 and was finally adopted more for its flexibility than for its superior accuracy. Using the original FHWA emission level functions, the model revealed a tendency for slight overprediction of noise along expressways when predicted and measured values were compared. Thus, it was decided to carry out a specific Ontario study on noise emission levels of vehicles.

The primary objective of the study was to develop and establish up-to-date vehicle noise reference energy mean emission levels for Ontario, as required and defined by the FHWA prediction model (2,6). These reference noise levels are also needed for simplified prediction methods that have been developed from the original FHWA model to serve the less sophisticated needs of, for example, environmental planners (7,8).

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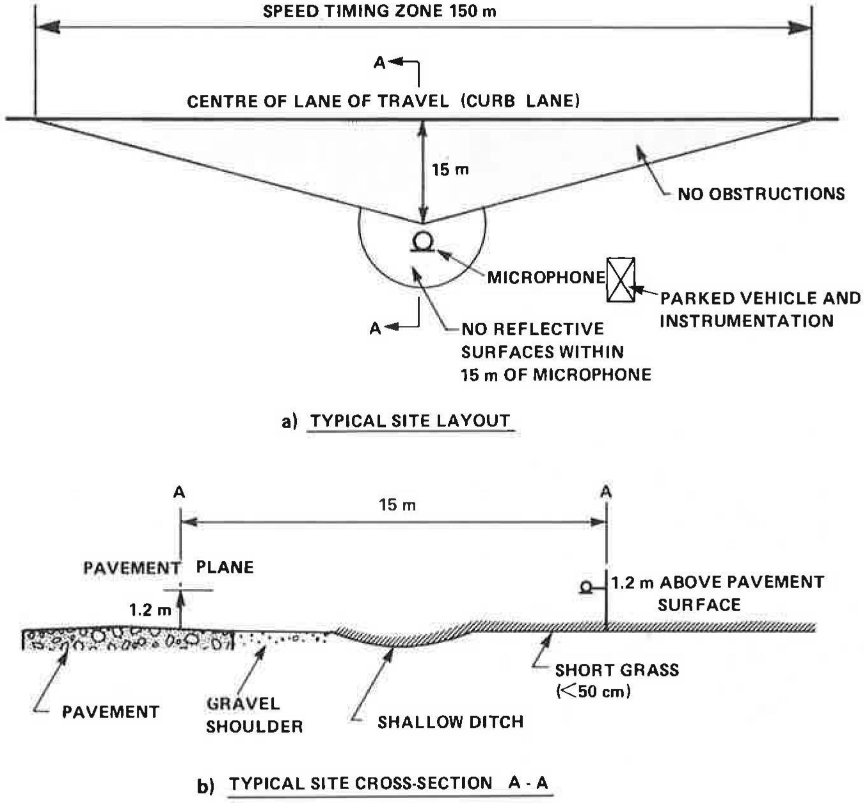


FIGURE 1 Typical layout of roadside measurements.

FIELD MEASUREMENTS

Test Sites

The basic requirements of a test site are shown in Figure 1a and 1b. The sites chosen for inclusion in the Ontario survey and a map showing the location of these sites are presented in Figure 2. The sound level measurement sites are spread over a wide cross section of the Ontario road system.

It was necessary to test a number of sites in order to include representative variation in pavement type, ground condition, vehicle type, and vehicle speed. All sites were located in an open level area free of obstructions such as parked cars, buildings, or sign boards, and all had low peak background sound levels more than 10 dBA below the lowest measured levels. Further, as a result of an investigation at the airport site with vehicles traveling on the runways, it was found to be very important to conduct measurements when the windspeed does not exceed a limit of approximately 20 km/hr.

The microphones at all sites were located 15 m from the center of the traveled lane and 1.2 m above pavement elevation. A clear line of sight was maintained between the microphone position and the roadway in both directions. All pavements were in fair to good condition. In short, measurements were carried out in accordance with the general requirements given by FHWA (9).

All measurement sites were in rural or quiet urban locations with low traffic volumes so that pass-

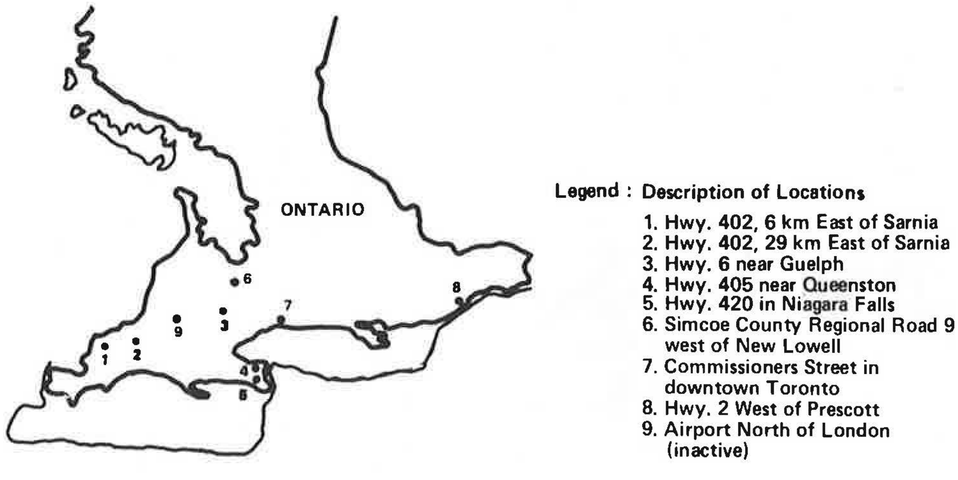


FIGURE 2 Single event (truck) on Highway 402.

FIGURE 3 Instrumentation of roadside measurements.

FIGURE 4 Sites of roadside measurements in Ontario.

ing vehicles could be measured independently, as single events (Figures 3 and 4).

Measurement Procedure

Before field measurements were made, the instruments were checked in the laboratory to ensure proper calibration. The instruments used in this procedure were as follows:

- Bruel and Kjaer (B&K) noise level analyzer, Type 4426
- B&K sound level meter, Type 2218
- B&K calibrator, Type 4230
- B&K alphanumeric printer, Type 2312
- B&K graphic level recorder, Type 2306
- B&K 1/2-in. microphone, Type 4165
- B&K 30-m microphone extension cable, Type A0 0029
- B&K microphone windscreen
- Uher tape recorder, Type 4200 Report Monitor
- Tripod

All of the sound level meters complied with the requirements for Type 1 precision instruments of the American National Standards Institute (ANSI S1.4, 1983).

Two sound level measurement systems were set up and calibrated on site with microphones placed at the same location, 15 m from the highway. The main reason for using two independent measuring systems is that one system can act as a check on the other, thus helping to avoid the possibility of introducing any gross errors in the measured sound levels. After initial calibration, a 10-min comparison test of the performance of the sound-measuring instruments using the noise emitted from the traffic on the nearby highway was done. The measuring systems were recalibrated approximately once every hour or sooner when necessary (for example, when batteries had to be changed in an instrument). The two measuring systems were constituted as follows.

System 1 consisted of a microphone and preamplifier placed on the end of a 30-m extension cable and connected to a B&K 2218 sound level meter. The AC voltage output from this meter was tape recorded on one channel of a stereo tape recorder and the other channel was reserved for comments about the vehicle passing by. The sound level meter in this system was not used to read the sound levels as the vehicle passed but only to condition the signal for tape recording. The recorded audio tapes were kept for evaluation at a later date in the laboratory.

System 2 comprised a microphone and preamplifier placed on a 30-m extension cable and connected to a B&K 4426 noise level analyzer. This system allowed for direct field evaluation of the sounds emitted from passing vehicles.

The maximum sound level measured as the vehicle passed was obtained from the noise analyzer in System 2. This, as well as the speed and type of vehicle, were recorded on data sheets in the field. The speed of the vehicle was measured by timing it over a 150-m (see Figure 1) distance. These data were later verified from information recorded on the audio tapes of System 1.

RESULTS

Data on vehicle noise emission levels were collected at various locations in Ontario, as shown in Figure 2, to obtain a representative set of pooled vehicle- and speed-related data for Ontario conditions. These data were processed in two ways with respect to groupings or classes of vehicles with similar levels of noise emission.

First, in accordance with the original FHWA report (1), vehicles were assigned to one of three classifications--heavy trucks (HT), medium trucks (MT), and automobiles (A), which includes other vehicles of similar noise emission. An accurate definition of these classes is given in the FHWA report (1,p.4).

Second, vehicles were further classified in accordance with groupings customary in Ontario, namely, by dividing them into long trucks (LT), short trucks (ST), and automobiles (A). These vehicle classes were introduced, not for acoustical reasons but because traffic data can be more readily obtained in these terms. The Ontario classes are shown in Figure 5, and a comparison between the Ontario and FHWA groupings of vehicles is given in Figure 6.

The measurements were sorted by speed classes (every 5 km/hr) as well as by vehicle type, and each group or cluster of measurements was statistically analyzed. The results are shown in Table 1, in which vehicles are classified according to the FHWA definitions (HT, MT, and A). The sample size for each speed and vehicle class is also shown, together with the mean and standard deviation of noise emission levels. The results for the second grouping by Ontario vehicle classes (LT, ST, and A) are similar and are therefore not shown in tabular form.

The data shown in Table 1 were subjected to a linear regression analysis in order to obtain the customary expressions for the reference energy mean noise emission levels of each vehicle class. The resulting curves are presented in Figures 7 and 8 for the FHWA and Ontario classes, respectively.

In Figure 9 the Ontario emission levels are compared with the originally published FHWA levels (1) (HT, MT, and A). The comparison shows that in Ontario trucks emit less noise at high speeds. On the other hand, automobiles are noisier, especially at lower speeds. Furthermore, medium-weight trucks are somewhat less noisy at higher speeds but slightly noisier at lower speeds. Since speeds of 80 to 100 km/hr are legal in Ontario, the aforementioned difference must lead to an overprediction of truck noise when the original FHWA emission level functions are used. The difference in car noise at high speeds is less significant.

Figure 10a, b, and c gives the statistical variations of the measurements and average values of emission levels in each speed class and vehicle

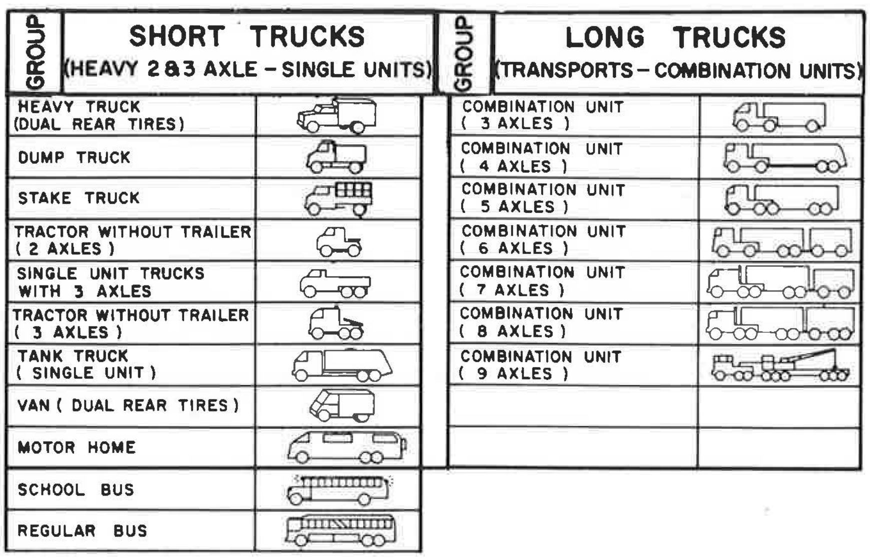


FIGURE 5 Short-truck--long-truck classification in Ontario.

	MTC SHORT TRUCKS SINGLE UNITS		MTC LONG TRUCKS COMBINATION UNITS
	MEDIUM TRUCKS	HEAVY TRUCKS	
AXLES	2 AXLES - 2 TIRES ON REAR AXLE	2, 3 & 4 AXLES - 4 TIRES ON REAR AXLE/S	3 OR MORE AXLES TRANSPORTS
WEIGHT	GENERALLY LESS THAN 5 500 kg	MAX. 38 300 kg	MAX. 63 500 kg
LENGTH		MAX. 12.5 m	MAX. 21 m
BODY STYLES	VANS, PICKUP	DUMP, STAKE, TANKER, BOX, TOW TRUCK	TRACTOR TRAILERS, FLATBED, TANKER TRAILERS, CAR CARRIERS

FIGURE 6 Comparison of classifications, Ontario and FHWA.

TABLE 1 Results of Field Measurements

	Speed Class	Noise Emission Level: Mean	Noise Emission Level: Standard Deviation	Sample Size
HT	40	79.2	2.9	15
	50	83.0	3.3	33
	60	82.8	2.4	35
	65	83.9	2.2	34
	70	84.7	2.7	52
	75	85.0	2.7	78
	80	83.9	2.2	106
	85	84.4	2.3	133
	90	84.9	2.4	119
	95	85.7	2.2	122
	100	85.9	2.4	88
	105	86.1	2.5	41
	110	85.9	1.8	29
Total				885
MT	50	75.2	4.0	19
	60	79.2	4.3	10
	70	77.7	3.3	15
	75	81.0	3.9	21
	80	80.0	3.5	29
	85	81.4	3.0	25
	90	82.5	3.9	35
	95	82.2	2.9	19
	100	83.0	3.9	15
	105	84.3	3.9	7
Total				195
A	50	64.5	2.3	10
	55	65.2	2.1	7
	60	67.9	1.9	13
	65	68.0	1.8	12
	70	70.9	2.2	30
	75	71.8	2.2	55
	80	72.4	2.2	100
	85	73.2	2.1	91
	90	73.0	2.1	138
	95	73.9	2.2	117
	100	73.9	1.5	112
	105	74.7	1.8	52
	110	75.0	1.7	60
	115	75.8	1.9	20
	120	76.7	1.4	6
	130	77.5	1.8	7
Total				830

Note: HT = heavy truck, MT = medium truck, A = automobile. Data are for all sites, pooled.

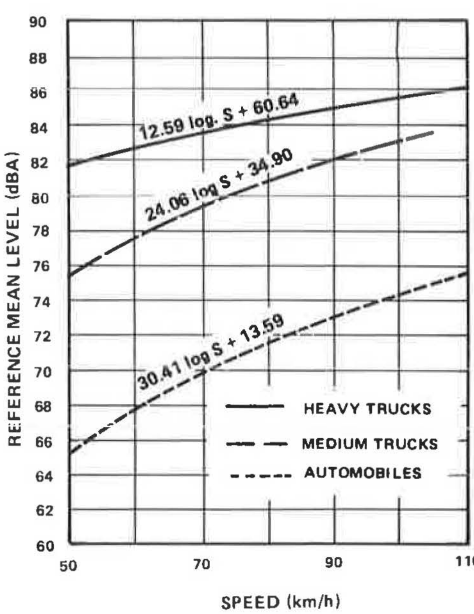


FIGURE 7 Emission levels of Ontario vehicles classified according to FHWA.

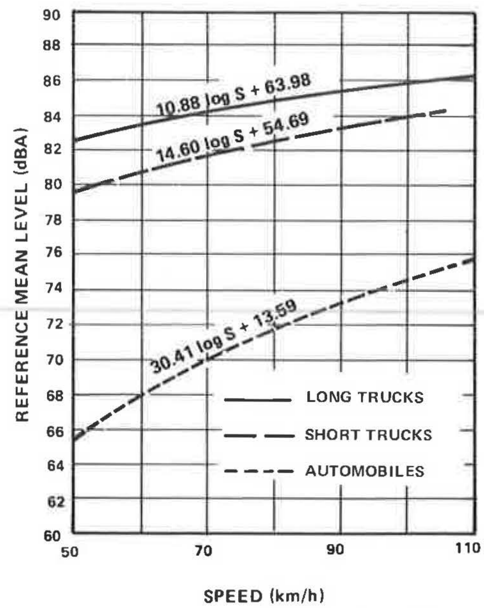


FIGURE 8 Emission levels of Ontario vehicles classified according to short trucks versus long trucks.

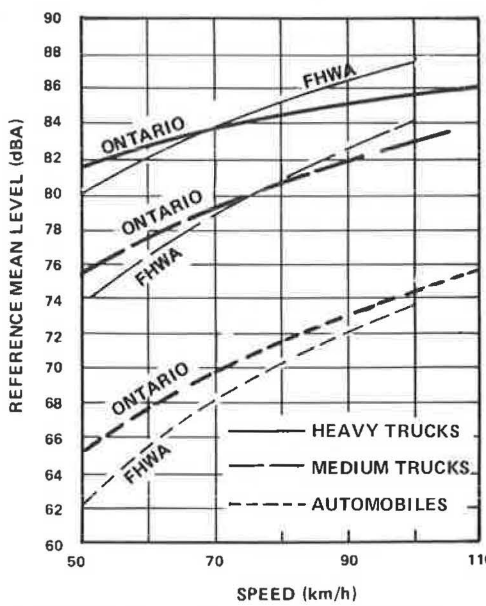


FIGURE 9 Comparison of Figure 7 emission levels with original FHWA levels (*1*).

group. The points of plus or minus one standard deviation (vertically) are also plotted. The vehicle groups used in Figure 10 are those defined by FHWA. The curves shown are regression lines identical to those in Figure 7.

The resulting equations for the reference energy emission levels as found from the 1984-1985 measurements in Ontario are listed in Table 2. This table can be used to provide new, up-to-date input for the various programs based on the FHWA model (1,5,8) when they are used in Ontario.

The effect of the new equations for Ontario is shown by a typical case (Figure 11), for vehicles traveling close to the legal speed limit of 100 km/hr. This example of an expressway in an urban

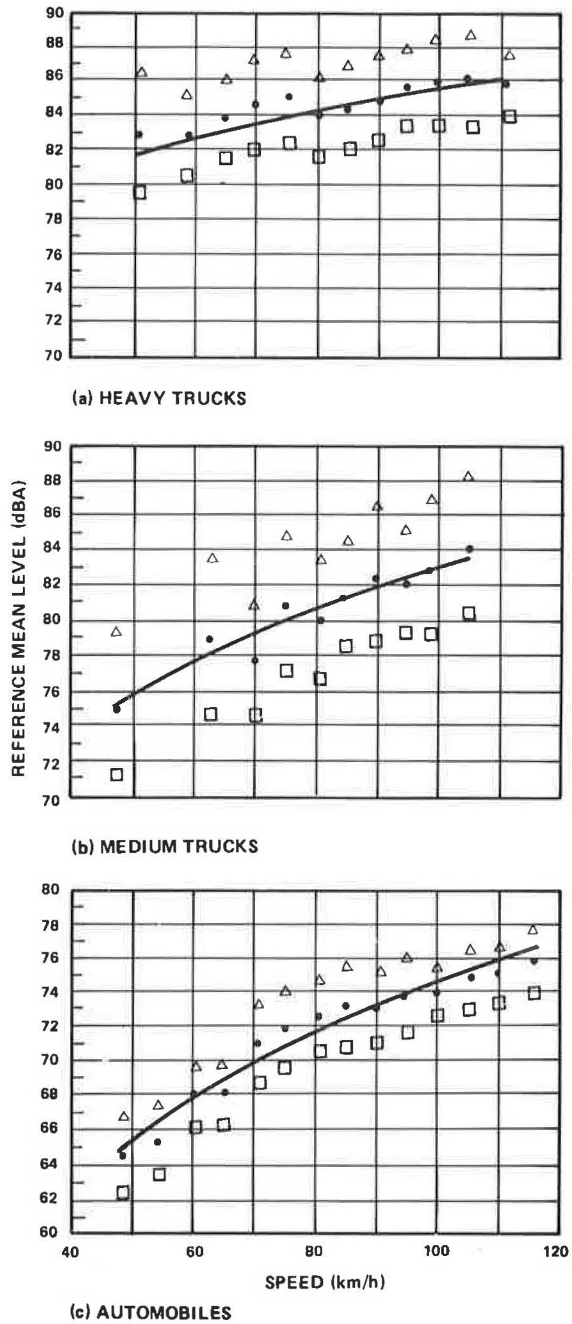


FIGURE 10 Standard deviations of emission level curves.

TABLE 2 Reference Mean Emission Levels in Ontario

Vehicle Class	Equation
Heavy trucks	12.59 logS + 60.64
Long trucks	10.88 logS + 63.98
Medium trucks	24.06 logS + 34.90
Short trucks	14.60 logS + 54.69
Cars	30.41 logS + 13.59

Note: S = speed (km/hr).

area consists of three westbound (R1) and three eastbound (R2) lanes. Predictions at 30 m and at 60 m from the near-lane center are compared. In both cases, the original FHWA equations predict noise 1 dBA above that predicted by the new Ontario equations. For lower speeds the difference will be smaller or will be reversed. For a larger percentage of trucks at 100 km/hr, the difference would be larger than 1 dBA.

DISCUSSION OF RESULTS

Statistical Problems

Single-event noise emission levels of vehicles were measured in terms of adjusted decibels, which is a logarithmic scale; therefore, the measured values must be converted to sound pressure energies before they are manipulated. The mean values of each sample in each speed and vehicle class were calculated as follows:

$$L_m = 10 \log \left[(1/n) \sum_{i=1}^{n} 10^{L_i/10} \right] \qquad (1)$$

where

L_i = noise emission level of a single event (dBA),
L_m = mean value of sample, average noise emission level (dBA), and
n = sample size.

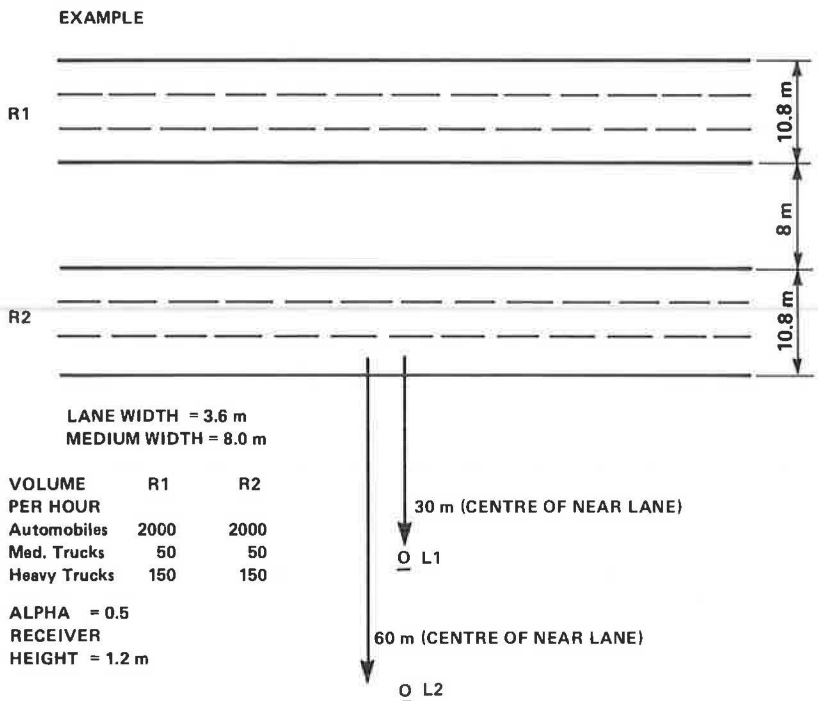
This method of calculating average values of noise emission levels is consistent with the definition of L_{eq}.

The normalized distribution of sound pressure energy for the Ontario heavy-truck population is shown in Figure 12. To obtain this distribution, the sample data from all heavy trucks traveling at speeds greater than 80 km/hr were normalized to a zero mean value in each speed group and then pooled. The pooling was possible because F-tests showed no statistically significant difference between the standard deviations of the different speed groups. Whereas Figure 12 shows the distribution of sound pressure energy measurements on a nonlogarithmic scale, Figure 13 gives the same information as normalized noise emission levels in terms of adjusted decibels, which is a logarithmic scale.

Both Figures 12 and 13 exhibit a long tail of high noise emission levels. The upper part of the tail, beyond 5 dBA above the mean value, represents only approximately 4 percent of the truck population, which contributes an additional 1/2 to 1 dBA to the average emission level of trucks. This represents about one-fifth of the sound pressure energy.

This 4 percent of unusually noisy trucks is intrusive in its noise impact compared with the general population, and from the shape of the distribution curves one may conclude that this may be due to unusual circumstances, such as faulty mufflers. More stringent enforcement of regulatory standards could discourage such high emission levels and would affect only 4 percent of the truck population.

With regard to the practice of noise measurements, the following should be pointed out. In a small sample size (such as that obtained by 20 min of measurement on roads of low traffic volume), those very noisy vehicles in the tail of the distribution curves will probably be missed. This would result in a lower average value of noise than would be representative for a 24-hr L_{eq}, the current Ontario standard of noise control. With the increasing sample size the measured average noise emission level would slowly increase because of the increasing probability of encountering those excessively noisy events from the tail of the distribution. Thus, measurements of 20 min duration at low traffic volumes may underestimate the 24-hr L_{eq} noise that is used as a standard duration of measurement in Ontario.



RESULTS	FHWA DATA (dBA)	ONTARIO DATA (dBA)	DIFF. (dBA)
L1	73.9	73.0	0.9
L2	70.1	69.3	0.8

FIGURE 11 Comparison of effect of new Ontario vehicle noise emission levels with that of original FHWA levels.

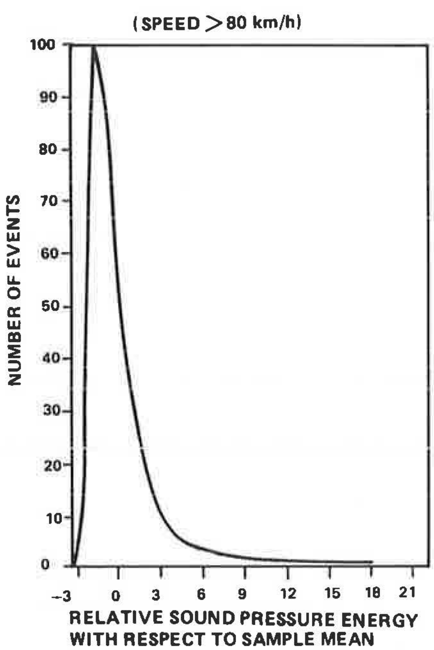


FIGURE 12 Heavy-truck noise distribution: energy.

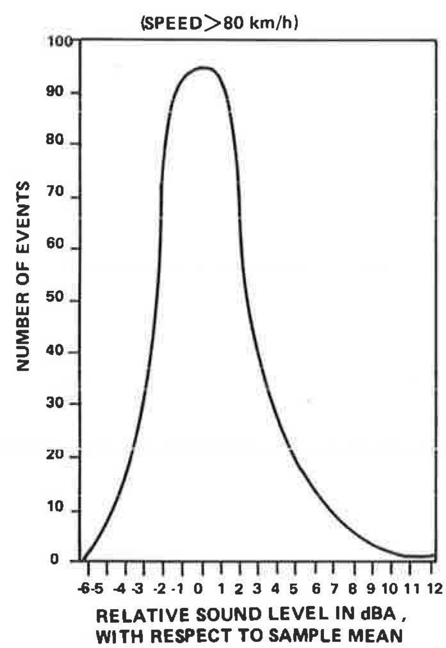


FIGURE 13 Heavy-truck noise distribution: adjusted decibels.

CONCLUSIONS AND RECOMMENDATIONS

Functions of reference energy mean emission levels with speed have been established for heavy trucks, medium trucks, and automobiles in Ontario. The levels are different from those currently used in the STAMINA program of the FHWA model. In particular, it has been found that heavy trucks are less noisy at high speeds, near the legal speed limit. Trucks and cars at low speed are noisier.

When using STAMINA or any other noise prediction program derived from the analytical FHWA model, new equations for reference emission levels should be used. For Ontario, these are as listed in Table 2.

Noise emission levels of vehicles should be regulated by establishing a legal maximum noise limit to exclude the rare events in the upper tail of vehicle noise distributions that have a high impact on noise pollution.

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Heavy-Truck Noise Emission Levels on Grades in California

RUDOLF W. HENDRIKS

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

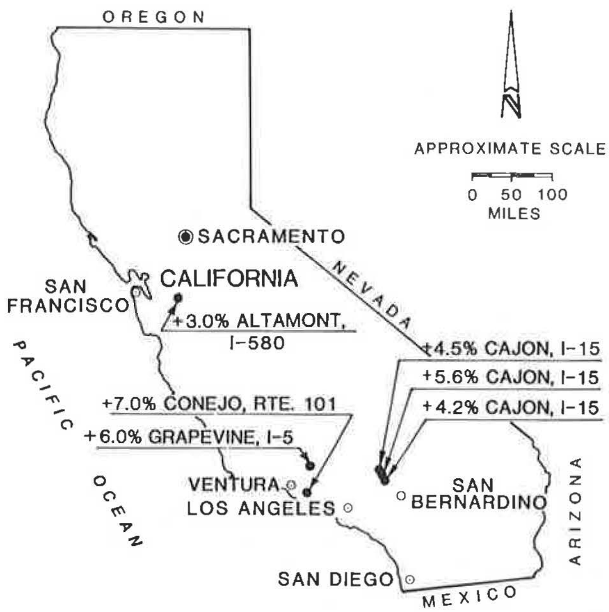

FIGURE 1 Locations of noise measurement sites.

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

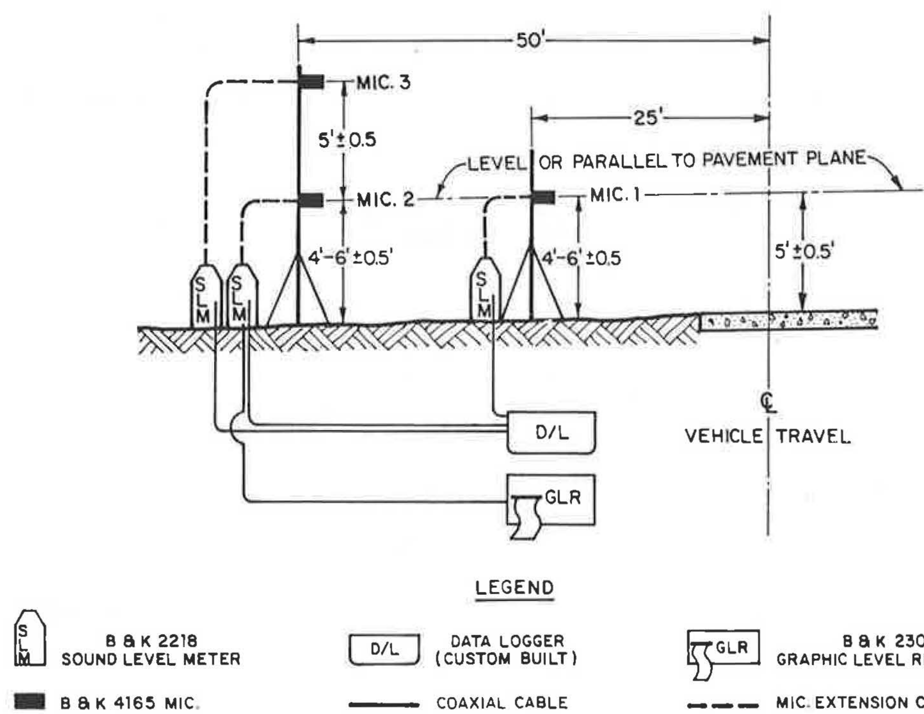

FIGURE 2 Typical setup for noise measurements.

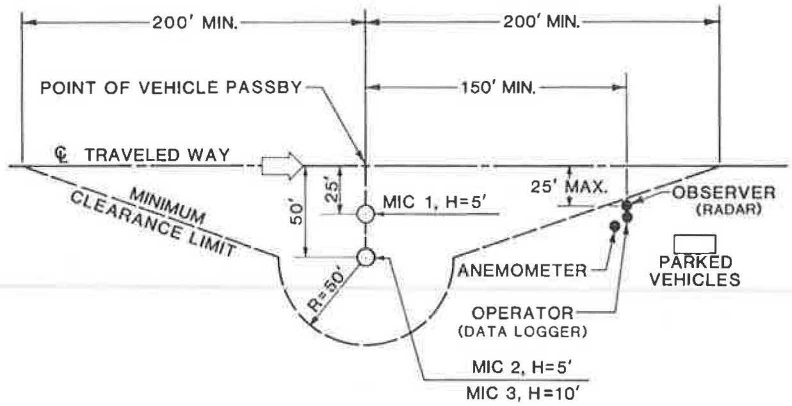

FIGURE 3 Typical site layout and microphone locations.

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-

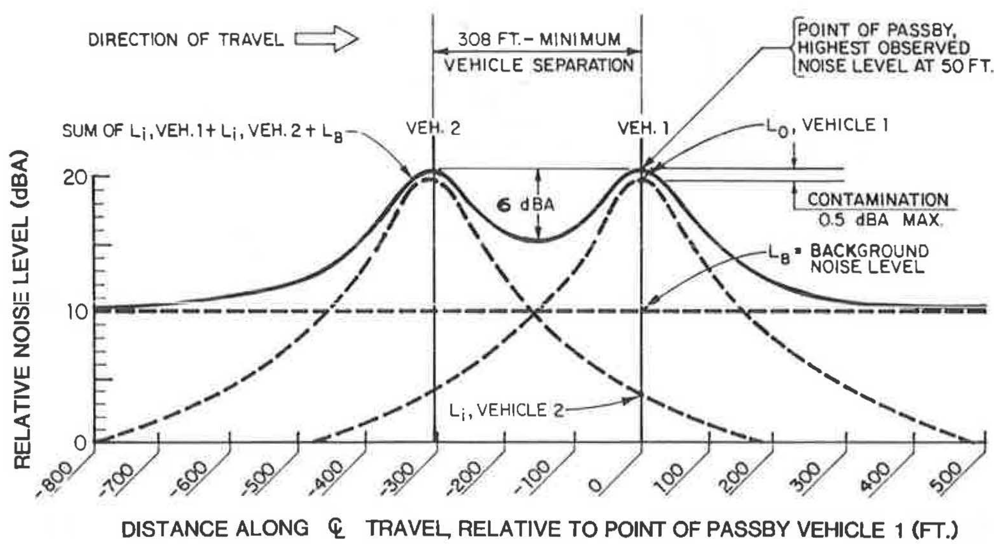

FIGURE 4 Minimum separation between two heavy trucks.

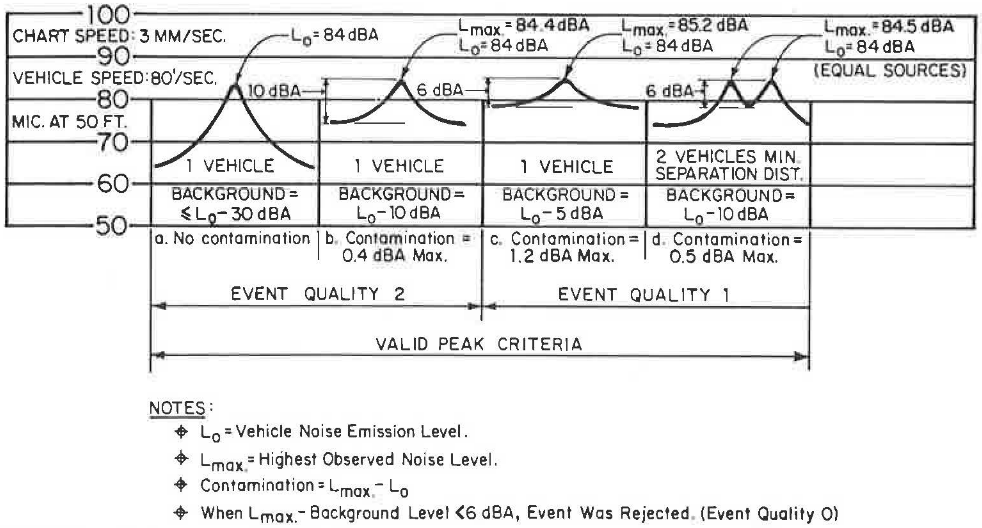

FIGURE 5 Valid peak and event criteria.

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

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

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.

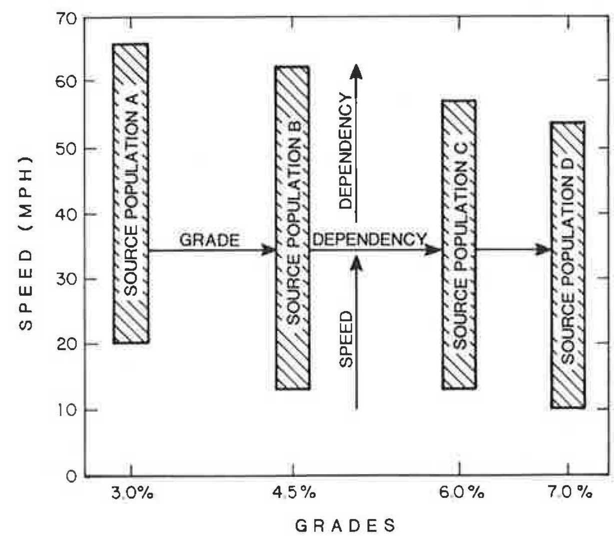

FIGURE 6 Speed dependency versus grade dependency.

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

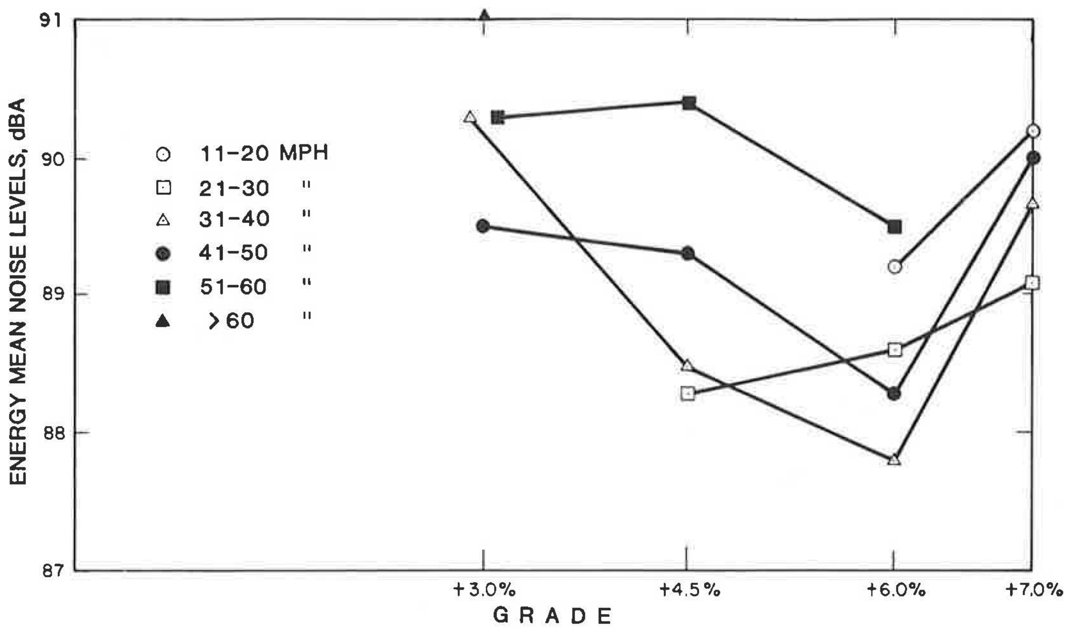

FIGURE 7 Energy mean noise levels at 25 ft versus grade by speed class.

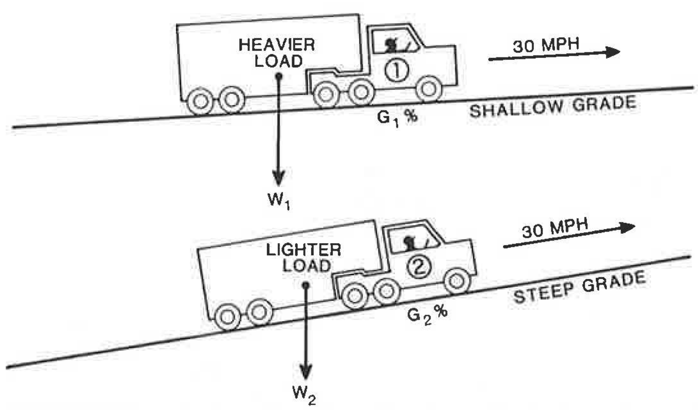

FIGURE 8 Sustained crawl speed as a function of load and percentage of grade ($G_1 W_1 \cong G_2 W_2$).

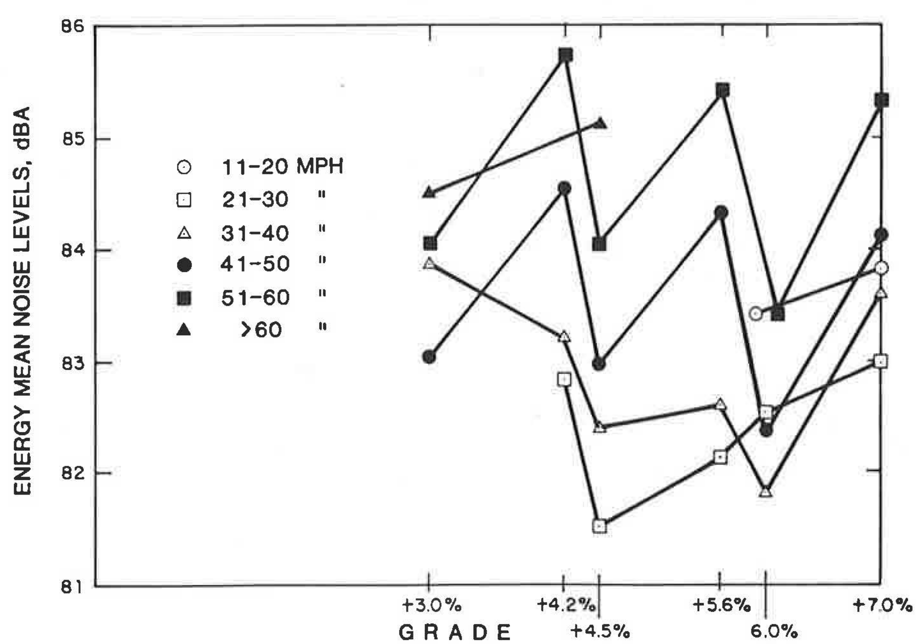

FIGURE 9 Energy mean noise levels at 50 ft versus grade by speed class.

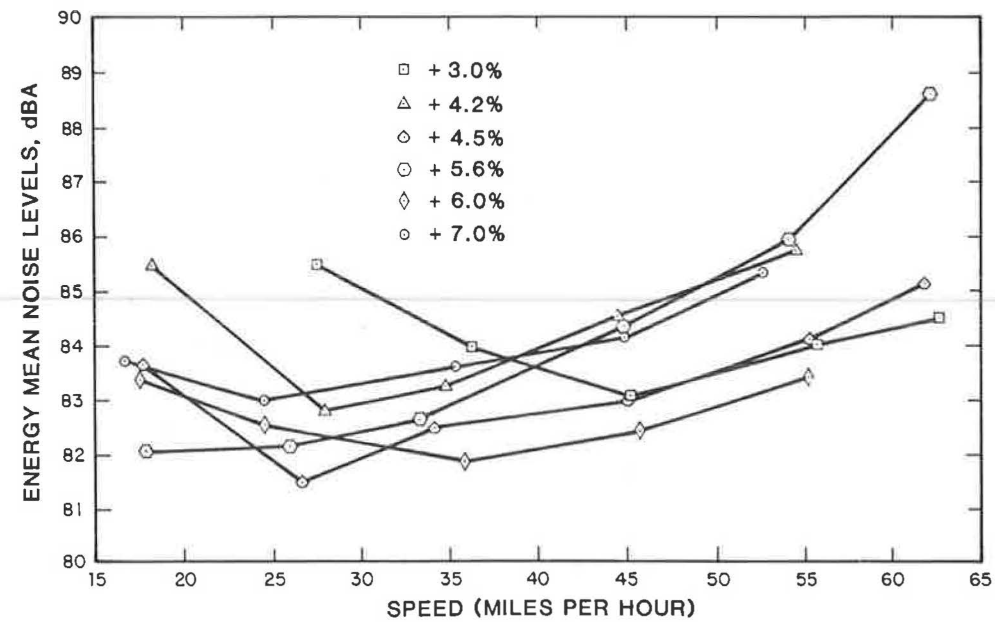

FIGURE 10 Plots by means of 10-mph speed classes (speed versus L_{eq}).

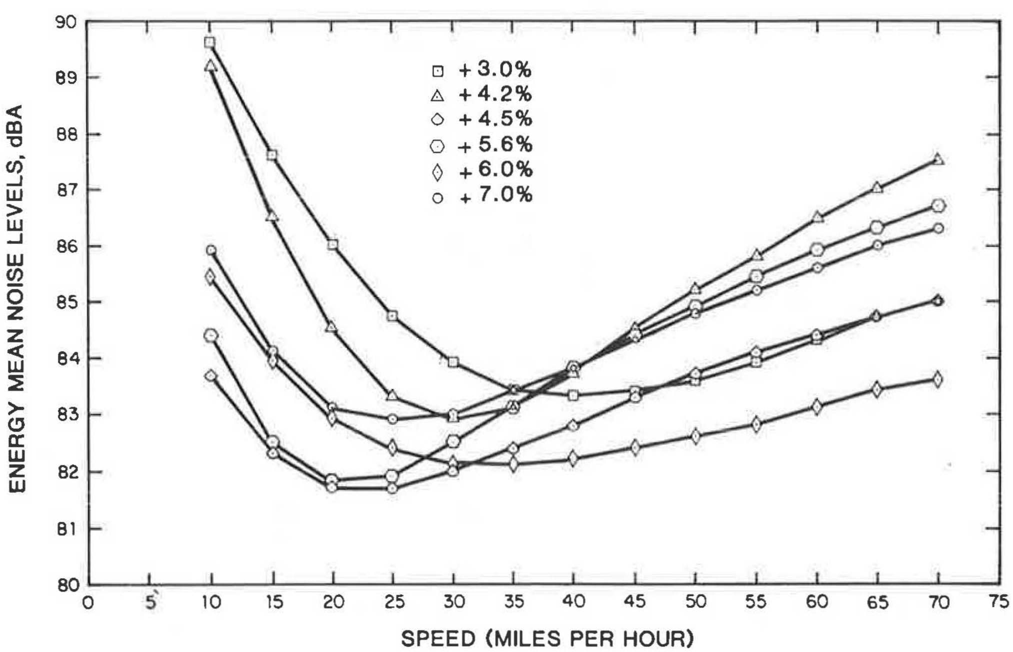

FIGURE 11 Energy averaged second-degree polynomial plots (individual sites, 50-ft data).

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

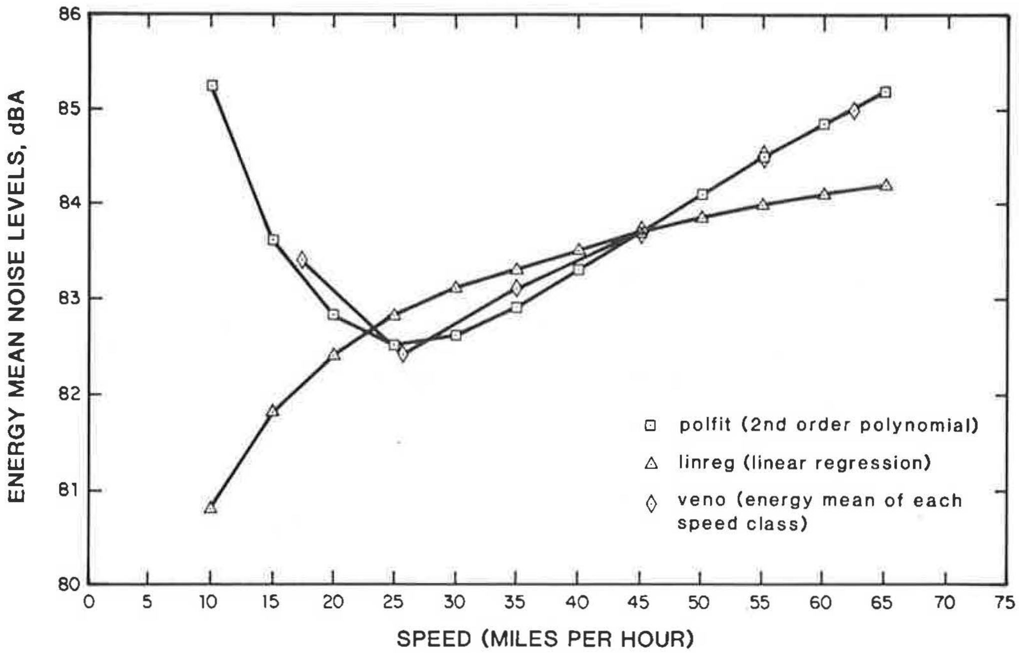

FIGURE 12 $L_{\overline{OE}}$ versus log speed, three methods (all sites combined, 50-ft data).

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-

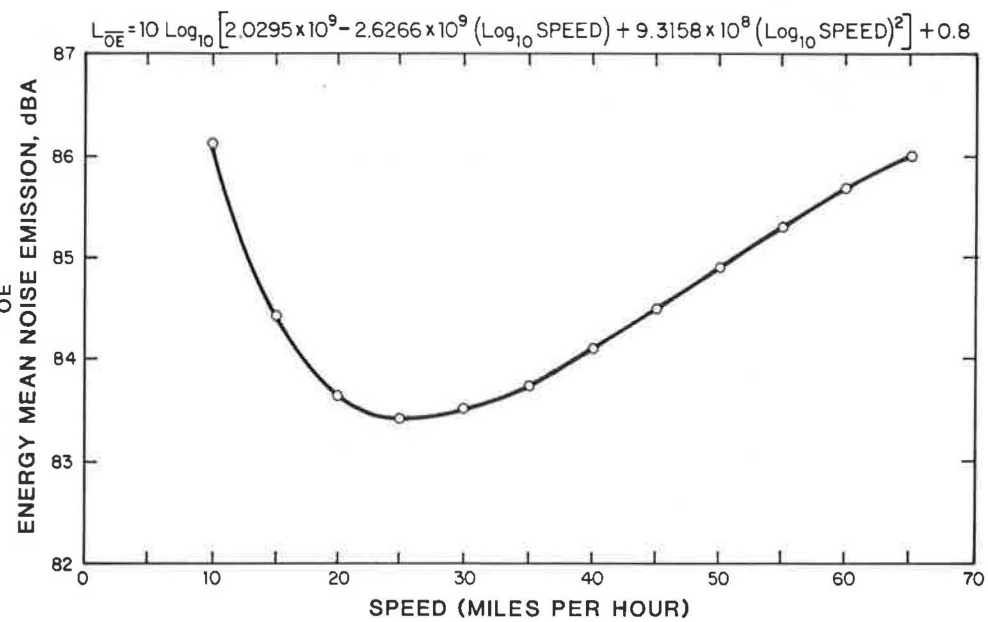

FIGURE 13 California heavy truck-on-grade noise reference energy mean emission levels, grades +3 to +7 percent.

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

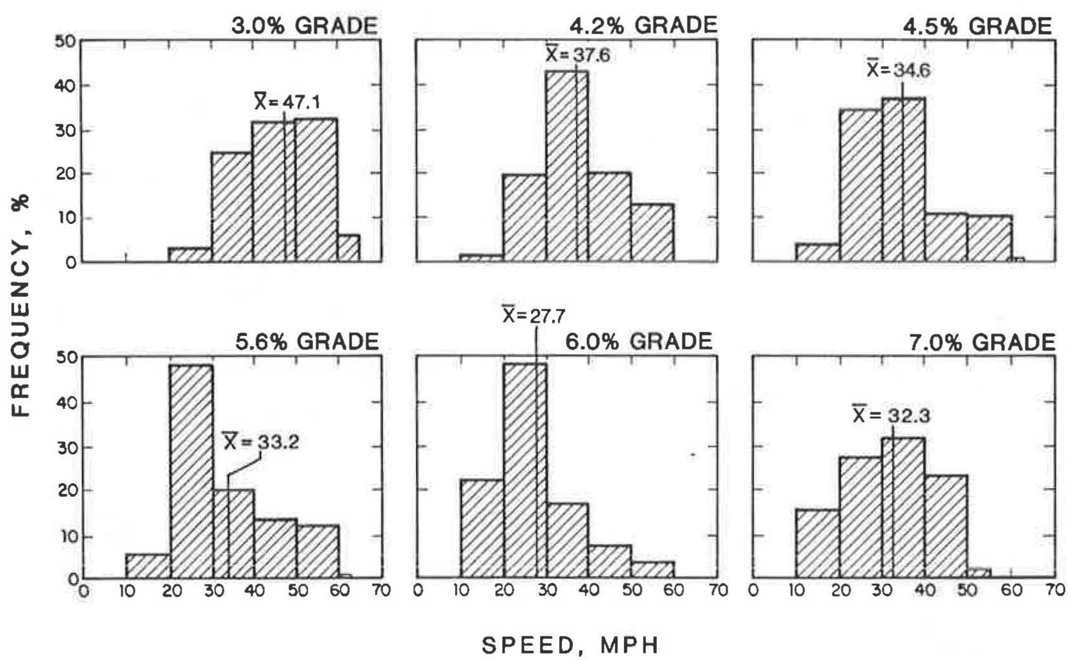

FIGURE 14 Speed distributions by grade.

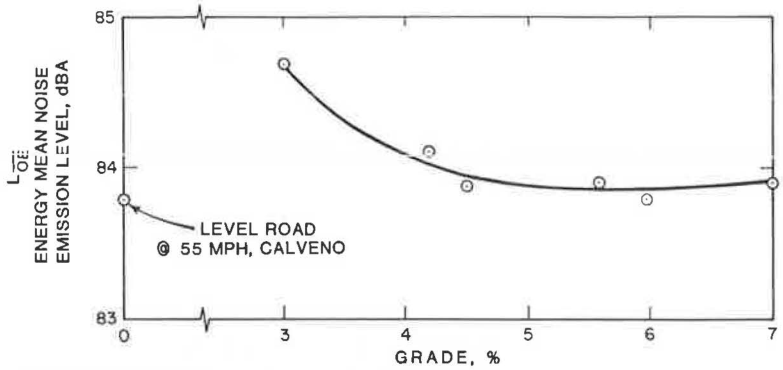

FIGURE 15 Weighted noise emission levels for observed speed distributions, heavy trucks uphill on +3 to +7 percent grades.

TABLE 7 Observed Versus Typical Speeds

	Average Truck Speed (mph)		12.5 Percentile Truck Speed (mph)	
Grade (%)	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

		Calgrade $L_{\overline{OE}}$ (dBA)	
Grade (%)	Avg Observed Speed (mph)	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

		$L_{\overline{OE}}$ (dBA) Based on Avg Speed	
Grade (%)	Avg Typical Speed (mph)	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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A Methodology for Assessing Highway Traffic Noise Impacts in an Airport Environment

JIMMEY BAILEY

ABSTRACT

A method used in predicting highway noise in conjunction with airport noise levels and assessing the total noise environment is presented. This method has been approved for use in Florida by the Federal Highway Administration. The method presented may not work for all similar situations; however, it does provide a starting point for innovations when manpower, monitoring equipment, and modeling programs are limited.

FHWA requires consideration of the impact of highway traffic-generated noise on land uses adjacent to a new or improved roadway. Of particular concern is the amplitude and duration of noise levels that research has shown to be either disturbing to normal functions associated with that land use or capable of producing adverse organic effects on the human aural system.

It makes little sense to seek reduction in or abatement of highway-generated noise levels for a particular receptor when other noise sources create levels as high or higher than those produced by automobiles and trucks on the roadway. Thus, it is important for the highway planner, engineer, or environmentalist to search out and identify all noise sources that affect the total noise environment of a particular land use and determine their composite and individual effects on the receptor.

HIGHWAY NOISE IN AN AIRPORT ENVIRONMENT

The Third District of the Florida Department of Transportation initiated studies to determine the best way to increase the capacity of 12th Avenue in Pensacola (Figure 1). Forecasts of network computer models indicated significant increases in the future highway traffic demand and no workable alternatives to the upgrading of 12th Avenue were determined to be available. Therefore, the recommended improvement was to make the existing roadway multilane. An environmental analysis was prepared to identify and address probable environmental impacts on natural and man-made elements of lands adjacent to the existing facility. Noise levels were identified as a probable major consequence because of the developed nature of much of the acreage along the existing route and the need for additional rights-of-way (Figure 2).

Field investigations of the area to obtain noise measurements for validation of computer models before their use in preparation of future noise level projections met with immediate difficulties. Pensacola Regional Airport is located adjacent to a portion of the existing roadway. Noise levels generated by aircraft landing and taking off at this installation conflicted with collection of existing traffic noise measurements. It was found that field measurements had to represent a series of "windows" during the times between aircraft activity. After numerous samples, sufficient measurements of existing highway traffic noise were obtained to allow validation of the computer models. However, it was recognized that the difficulty experienced in collection of field measurements also indicated that noise levels generated by the airport operations play a significant role in the noise environment along this project.

It was realized that the airport had a significant impact on the noise environment and that it was necessary to obtain information concerning existing and future noise levels emanating from the airport and the relationship of these levels to the total noise environment. The Federal Aviation Administration (FAA) requires that airports receiving FAA monies prepare noise studies establishing noise impact zones of various magnitudes. The city of Pensacola's Planning Department had prepared an extensive document for the Pensacola Regional Airport. This document, Airport Noise Compatibility Program (1), establishes noise impact zones and detailed noise footprints based on the locations of the airport's runways, which runways were designated for primary use in landings and take-offs, and the types of aircraft using and expected to use the airport.

The airport noise study had been completed in late 1982 and the environmental study for the roadway improvement project was initiated in mid-1983. Therefore, the findings of the airport noise study were accepted as a given against which noise studies for the roadway could be compared and analyzed. (The noise study had been performed with assistance of the Florida Department of Transportation and had been accepted by the department and the FAA.)

Noise level predictions found in the airport noise study used the L_{dn} descriptor. The L_{dn} (day-night level) system is a classification methodology developed by the Environmental Protection Agency for the purpose of assessing noise impacts produced at any time of day. It is based upon the A-weighted sound pressure scale, which is weighted to compensate for the human ear's sensitivity to different sound pitches. Basically, the L_{dn} value for a particular geographic point is the daily average A-weighted sound pressure level existing at that point with those noises occurring between 10 p.m. and 7 a.m. penalized by an additional 10 dBA (10 dB are added to measurements or projections for these hours). Because highway traffic noise levels are usually measured with the L_{eq} descriptor, a direct comparison of the two noise sources did not appear

Florida Department of Transportation, Chipley, Fla. 32428-0607.

PROPOSED 12TH. AVE.

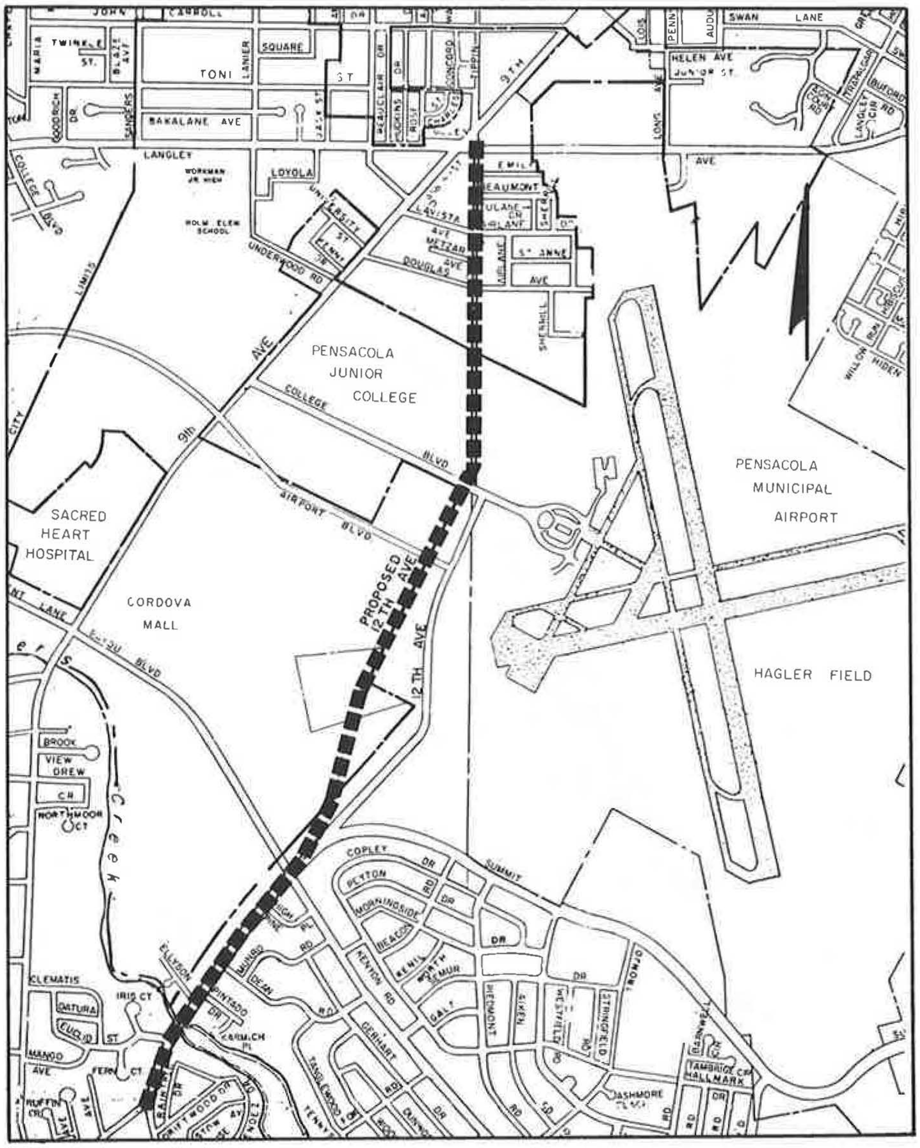

FIGURE 1 Project location map.

possible. L_{eq} is defined as "the equivalent steady-state sound level which in a stated period of time contains the same acoustic energy as the time-varying sound level during the same period" (2).

Because sufficient time, manpower, and equipment were lacking to conduct a 24-hr noise study in the field to determine the L_{dn} and because the difficulty of doing so in the airport environment was recognized, an alternative method had to be devised to allow an L_{eq} versus L_{dn} comparison. This led to the development of a methodology that, although conservative, allowed for this comparison without the extensive use of either manpower or equipment.

The first step was to determine the traffic characteristics of 12th Avenue in the vicinity of the airport. This was done by using a traffic counter set to provide an hourly readout of traffic volumes. The results of this effort can be found in Table 1. It becomes readily apparent from examining these counts that there are significant differences in traffic volumes utilizing the roadway during the nighttime penalty hours as opposed to the daytime hours. This difference became the basis for the development of the methodology described.

With the traffic data gathered by the counter, it was decided that field traffic noise measurements would be conducted from 4:00 to 5:00 p.m. Because this was the peak traffic hour, the hourly $L_{eq}(h)$ should represent the worst-case condition. This measurement was used as an upper limit to the 24-hr L_{dn}. The L_{dn} will in fact be the same as the peak-hour L_{eq} if (a) the hourly L_{eq} for each daytime hour is the same as the peak-hour L_{eq}, and (b) the hourly L_{eq} for each nighttime hour is 10 dB less than the peak-hour L_{eq}. The first assumption is obviously conservative, because all other daytime hourly L_{eq}'s are less than the peak-hour L_{eq}. The second assumption requires more consideration.

A simple estimate of the hourly L_{eq} during the nighttime hours can be made by considering the difference in traffic volume between the peak hour and the nighttime hours. As can be seen in Table 1, the average nighttime traffic volume is less than 1/12 of the peak-hour traffic volume. Because a noise

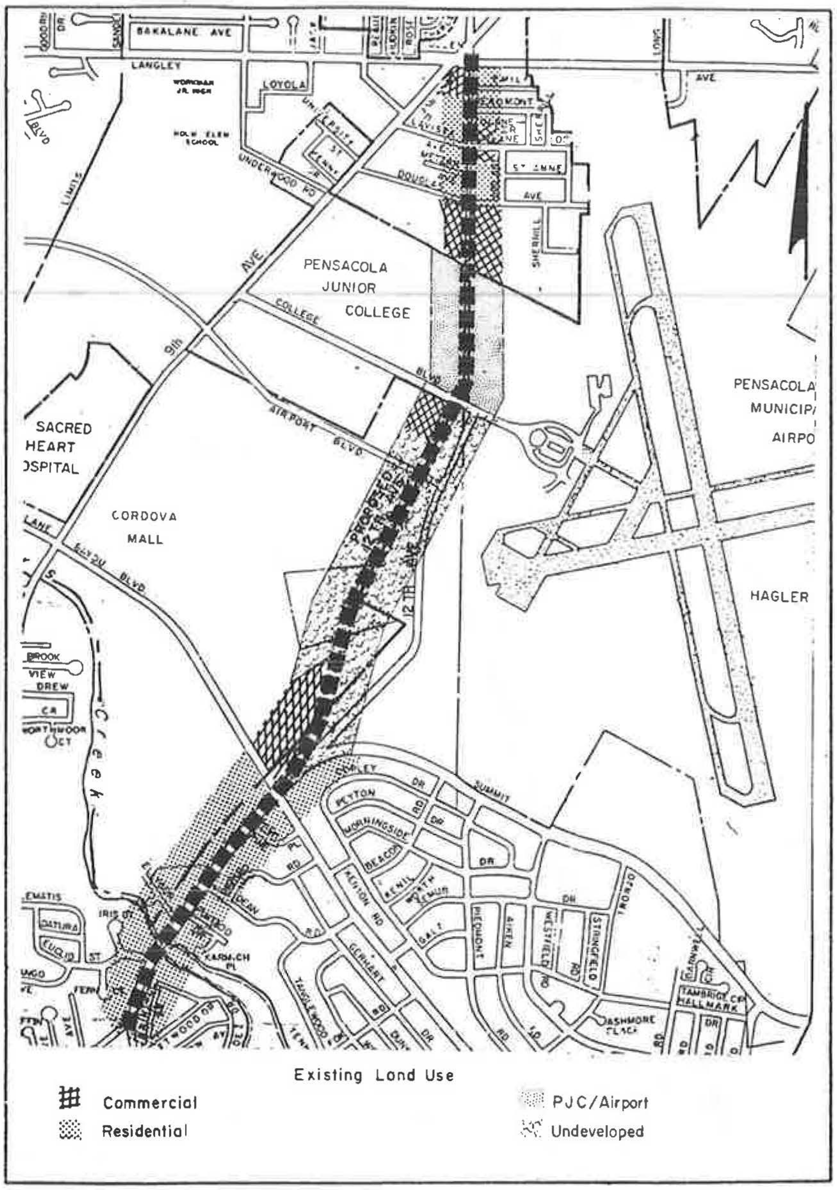

FIGURE 2 Existing land use map.

TABLE 1 Traffic Counts for 12th Avenue (24 hr)

Daytime	Measured Traffic Volume	Nighttime	Measured Traffic Volume
7-8 a.m.	1,318	10-11 p.m.	349
8-9 a.m.	1,219	11-12 a.m.	194
9-10 a.m.	1,131	12-1 a.m.	116
10-11 a.m.	1,022	1-2 a.m.	31
11-12 p.m.	1,225	2-3 a.m.	36
12-1 p.m.	1,220	3-4 a.m.	32
1-2 p.m.	1,178	4-5 a.m.	31
2-3 p.m.	1,458	5-6 a.m.	127
3-4 p.m.	1,513	6-7 a.m.	401
4-5 p.m.	1,761		
5-6 p.m.	1,600		
6-7 p.m.	1,128		
7-8 p.m.	841		
8-9 p.m.	618		
9-10 p.m.	570		
Total	17,802		1,317
Avg	1,187		146
Peak hour	1,761		401

level decreases by 10 dB if its source strength decreases by a factor of 10, the average hourly L_{eq} during the night in this case is more than 10 dB below the peak-hour L_{eq} and the second assumption is also conservative.

Because both assumptions are conservative, one can say with confidence that the L_{dn} is less than the peak-hour L_{eq}. Use of this approach to determine future traffic noise levels and the need for abatement efforts proved to be valuable because of the lack of automated noise-sampling equipment that could be used for total traffic cycles. This method also eliminated the need for additional manpower to conduct the 24-hr tests. This was extremely important because the manpower was not readily available and there was a tight time frame for project completion.

Comparison of L_{dn}'s for highway and airport noise indicated that the amplitude of highway traffic noise was less than that generated by aircraft for most of the length of the proposed project periods.

Where traffic noise was found to be predominant, it was analyzed and addressed according to procedures in the Federal-Aid Highway Program Manual (2).

Alternative methods to achieve similar results were also developed after the hectic push to complete the project had subsided. One of the methods uses a computer prediction of the daytime peak-hour L_{eq} and a similar prediction of the nighttime peak-hour L_{eq}. If the difference between the two levels is equal to or greater than the 10-dB penalty, the L_{dn} can be assumed to be less than the daytime peak-hour L_{eq}.

A second method would employ the computer prediction of the hourly L_{eq} for each daytime and nighttime hour. This would allow for the addition of the 10-dB penalty to each nighttime hour and then the 24-hourly predictions could be averaged to determine the L_{dn}. This would allow for a direct comparison of the contribution of noise from both highway and airport sources.

SUMMARY AND CONCLUSIONS

The methodology described used an existing noise study prepared for the airport to help establish and evaluate the total future noise environment along the highway project. Use of the airport noise study and this procedure also eliminated the need for additional noise sampling equipment and manpower to obtain field data throughout the 24-hr period.

This methodology was approved by the Florida FHWA office for this particular project. Approval for similar applications will have to be sought on a project-by-project basis. Before this approach is used for a unique noise situation, approval from the local FHWA office must be obtained.

ACKNOWLEDGMENTS

The contributions of several Florida Department of Transportation professionals that made this paper possible need to be recognized. Special recognition is due Gordon Morgan and Win Lindeman of the Bureau of Environment for their guidance and encouragement. A note of gratitude is also due Felter Alderman of Chipley for his help in the field measurements and analysis. To each of these gentlemen and others unnamed goes a tip of the hat. Thanks to Frank Roberts for the graphics and Rita Gilbert for the typing.

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Considerations for Modeling of Aircraft Noise

JERRY E. ROBERTS

ABSTRACT

Noise continues to be a major environmental problem at airports throughout the country. A brief review is given of the federal actions that have occurred over the last 30 years in attempts to reduce and abate aircraft noise impacts. The current Federal Aviation Administration (FAA) emphasis on land use compatibility studies is noted. An overview and simple sensitivity analysis of the primary airport noise analysis tool--the FAA's Integrated Noise Model (INM), is presented. The analysis includes the effects of aircraft type, stage length, airport elevation, and temperature selection. By reviewing the results of this analysis, users of the INM can increase their awareness of the sensitivity of the generated noise contours to input variables.

Although it may be argued that concerns over aviation noise were originated by some beachgoers near Kitty Hawk, North Carolina, on December 17, 1903, it is widely noted that the federal government began addressing the aircraft noise issue in the early 1950s. According to Foster (1), the U.S. Air Force first initiated research and development programs aimed at controlling aircraft noise in 1952.

There was little governmental coordination until 1965, when the President's Office of Science and Technology formed the Jet Aircraft Noise Panel, which directed a program to reduce the noise impact. Initiatives from the panel were assisted by an interagency program of aircraft noise control established as part of the Transportation Act of 1966. Formal regulatory authority to protect the public from unnecessary aircraft noise and sonic booms was given to the Federal Aviation Administration (FAA) under the Aircraft Noise Control Act in 1968.

In 1972 the Noise Control Act brought the Environmental Protection Agency into the picture in an advisory role. This act directed the FAA to prescribe regulations that were economically reasonable, safe, and technically practical for effectively controlling and abating aircraft noise. Subsequently, major legislation, funding, research, and development focused on source control, in particular with Federal Aviation Regulation (FAR) Part 36 requirements between 1969 and 1977. The effects became apparent through the 1970s and into the 1980s.

Specifically, in 1969, FAR Part 36 noise standards were applied to aircraft of new design such as the DC-10 and L1011, which are significantly quieter than the first-generation turbojet aircraft. After their feasibility had been demonstrated, the noise standards were extended in 1973 to new production airplanes. As a result, 727 and DC-9 aircraft manufactured since 1973 had to meet the 1969 standards. In 1976 the same noise standards were applied to all larger civil turbojet aircraft including those designed before 1969 and manufactured before 1973.

The stringency of the standards was increased in 1977 for new aircraft designs such as the 757 and MD-80. The new standards are commonly referred to as Stage 3 limits; Stage 2 limits are those initially adopted in 1969, and Stage 1 are aircraft that are unable to meet either of the noise standards. As of January 1, 1985, only aircraft that meet Stage 2 or Stage 3 may operate in the United States without an exemption. Since 1973 only aircraft that meet Stage 2 standards have been produced and since 1977 only Stage 3 aircraft have been approved for new design.

As newer and quieter aircraft were being introduced into the fleet, a general trend of reduced noise exposure around airports, even with increased operations, was projected. However, the effects of the Airline Deregulation Act of 1978 disturbed this trend. The older and noisier aircraft were not being retired, but were being used more and more by small air carriers.

In a statement before the House Subcommittee on Transportation, Aviation, and Material (West Palm Beach, Florida, April 1, 1985), John Wesler, Director of FAA's Office of Environment and Energy, explained why the problem persists and the difficulties in obtaining added compliance with stricter standards:

> There are approximately 2,900 larger commercial airplanes now in use by U.S. air carriers, and over 100 in use by private operators. Of these, approximately 350 were designed for and meet the Stage 3 noise limits. Perhaps 200 more in current use could meet that standard with minimal modifications or weight limitations. This leaves on the order of 2,350 larger aircraft which would have to be retired completely from U.S. service and replaced by new models or re-engined, since the use of "quiet nacelles" or "hush kits" cannot reach Stage 3 noise performance. The only aircraft currently being re-engined are the Douglas DC 8-60 series, which comfortably meet the Stage 3 noise standards with new engines. Many of the existing Stage 2 aircraft are relatively new and have a great deal of useful life left. Consequently, the reasonableness of such a major replacement of re-engining program is obviously one which requires a great deal of study and discussion.

The passage of the Aviation Safety and Noise Abatement Act (ASNA) of 1979 provided the foundation for a parallel effort toward source control by bringing the FAA into the land use compatibility arena. ASNA required the FAA to identify land uses normally compatible with various exposures of noise

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and to promulgate regulations for airports to voluntarily submit noise exposure maps and compatibility and control programs for dealing with expected noise impacts.

FAR PART 150

In response to ASNA, the FAA issued FAR Part 150, Airport Noise Compatibility Planning (interim rule, 1981; final rule, 1985), which prescribes the requirements for airports for which noise maps and planning programs are to be submitted. The procedures are a formal and legal outgrowth of the FAA's prototype Airport Noise Control and Land Use Compatibility (ANCLUC) programs of 1977-1982. The purpose of the program is twofold. First, it gets the airport operator to identify present and future noise patterns and noncompatible land uses around the airport (noise exposure maps), so that some degree of legal protection through constructive knowledge is established for subsequent actions. Second, a program is formulated of solutions to the noise problems identified by the noise maps. The solutions take the form of operational controls, such as flight path location and preferential runway usage, or land use planning techniques such as zoning and acquisition.

As an incentive to get airports to voluntarily comply with FAR Part 150, the Airport and Airway Improvement Act of 1982 provided for not less than 8 percent of the Airport Improvement Program (AIP) funds to be used for noise compatibility planning and programs following ASNA. For an airport to use federal AIP funds for noise projects, the airport must conduct a FAR Part 150 study. After formal review and finding by the FAA that the program meets ASNA provisions, noise abatement and mitigation actions detailed in the plan become eligible for AIP noise funds. In 1984 the amount available for noise compatibility programs was $64 million.

Noise planning meeting the criteria contained in FAR Part 150 is eligible for 75 percent federal funding to primary airports enplaning 0.25 percent or more of the total number of passengers enplaned annually at all commercial service airports (i.e., major and medium hubs) and 90 percent federal funding for all other commercial service and public-use airports. Measures designed to achieve compatible land use or attenuate noise or both that are included in approved programs, such as land acquisition and soundproofing, are eligible for 80 percent federal assistance.

Thus, the major efforts being put forth today by the FAA and airport operators are to identify the noise around airports and to plan for its control. To do this, the FAA has developed standardized noise planning tools and methods. In particular, the L_{dn} or DNL (day-night noise level) metric was selected as the choice for determining average noise exposure around an airport. The FAA has also developed a computer program to predict noise exposure levels around an airport based on aircraft operational and sound level data. The program, Integrated Noise Model (INM), provides a means for determining existing and future noise levels under a variety of alternatives. It is the key tool for conducting a FAR Part 150 study. In fact, FAR Part 150 requires that only the INM or an FAA-approved equivalent be used for noise compatibility planning studies.

INM BACKGROUND

The INM is a computer-based mathematical model used for predicting total impact of aircraft noise at and around airports. The INM calculates noise exposure from information provided by the user (physical layout of airport runways and flight tracks, any nonstandard alternate operational or performance data, frequency and time of operation) and data contained in the model (aircraft noise levels, operational and performance data). Results can be expressed for a variety of noise metrics either at specific receiver locations or as contours of equal noise exposure for selected values.

Version 1 of the model was released in 1978. It had a limited data base but provided the first step toward consistency in aircraft noise analysis. The following year, the FAA released Version 2, which expanded the aircraft data base and input options. In 1982 the currently used Version 3 was issued. It included further enhancements for determining noise impacts and updated the data base of aircraft noise levels and performance. A fourth version is under development with special emphasis on tasks to produce a fully standardized method of calculating airport noise (2).

The identification of a noise metric and the refinements of a selected model are necessary and proper steps for obtaining consistency in the determination of aircraft noise impacts. However, even with a completely accurate model, there is great latitude in the use and application of the model. The user has complete control over the selection of the scenario he wishes to model. Associated with this are the assumptions made to represent the scenario. These include the determination of what constitutes the time period (average or peak day) to be modeled, the description of flight tracks or corridors, the selection of typical aircraft from the data base, determination of operational conditions, and the projection of future operations and conditions. The dictum "garbage in equals garbage out" is highly appropriate. The following discussion focuses on the major areas of user choice in running the INM and the possible effects of those choices.

DATA BASE LIMITATIONS

The INM data base (3) has a selection of 66 aircraft, including commercial, military, and general aviation types. Associated with each aircraft is at least one of 38 sound exposure level (SEL) curves that describe thrust-distance-noise relationships. In addition, there are 56 approach profiles and 199 takeoff profiles in the data base that describe velocity, altitude, and thrust level as a function of horizontal distance from a reference point.

The proper selection of an aircraft and its operational characteristics is dependent on the best determination of those aircraft that use the airport compared with those available in the model. Earlier aircraft noise impact analyses generally considered aircraft as one of the following:

Two-engine narrow body	(DC-9, B737)
Three-engine narrow body	(B727)
Four-engine narrow body	(B707)
Three-engine wide body	(DC-10/L1011)
Business jet	(Lear)

Standard take-off and approach profiles were assigned to all aircraft. Whatever was produced by the computer program was generally accepted as the truth. Because the selectivity was limited, consistency may have been good, but reality could be far away.

Today the flexibility of the INM allows for more refinement of the aircraft selection process. For example, the variety of common narrow-body commer-

TABLE 1 Common Narrow-Body Jet Aircraft in INM Data Base 8

Type	INM Name
Four engines	
DC-8-50/JT3D-3	DC850
DC-8-60/JT3D-7	DC860
DC-8-60/CFM-56[a]	DC8CFM
DC-8-60/JT3D-7QN	DC8QN
Three engines	
B727-200/JT8D-7	727200
B727-100/JT8D-7	727100
B727-200/JT8D-15	727D15
B727-200-JT8D-9QN	727Q9
B727-100/JT8D-7QN	727Q7
B727-200/JT8D-15QN	727Q15
B727-200/JT8D-17	727D17
Two engines	
BAC111/SPEY512	BAC111
DC-9-30/JT8D-9	DC930
DC-9-10-JT8D-7	DC910
DC-9-30/JT8D-9QN	DC909
DC-9-10/JT8D-7QN	DC907
DC-9-50/JT8D-17	DC950
DC-9-80 (MD-80)/JT8D-209[a]	DC980
B737/JT8D-9	737
B737/JT8D-9QN	737QN
B737/JT8D-17	737D17

[a]Narrow-body aircraft with high-bypass-ratio jet engines.

cial aircraft available in the model is listed in Table 1. The choice is dependent on the aircraft series and engine configuration. Selecting an aircraft from this group is often not an easy choice because it is difficult to determine the exact series and engines of aircraft using an airport. For example, the most prolific and noisiest engine, the JT8D, was manufactured in over 10 different configurations; FAA registration figures show over 75 models of the B727.

To a lesser degree, the problem is also evident for wide-body aircraft, as shown in Table 2. It should be noted that the recently introduced B757 aircraft, although not actually considered a wide body, uses the quieter high-bypass-ratio engines characteristic of the wide-body fleet. A similar situation exists for the new MD-80 (DC980), which is not a wide-body aircraft and technically does not have high-bypass-ratio engines but produces significantly less noise than relative aircraft. With the new-generation aircraft entering the national fleet, the old generality that a narrow body is loud and a wide body is quiet is no longer valid.

TABLE 2 Common Wide-Body Jet Aircraft in INM Data Base 8

Type	INM Name
Three engines	
DC-10-10/CF6-6D	DC1010
DC-10-30/CF6-6D	DC1030
DC-10-40/JT9D-20	DC1040
L1011/RB211-22B	L1011
L1011-500/RB211-524	L10115
Two engines	
A300/CF6-50C	A300
B767/CF6-80A	B767
B757/RB211-535C[a]	757RB
B757/JT10D[a]	757JT

[a]Narrow-body aircraft with high-bypass ratio jet engines.

The same problem exists for business jet aircraft. Table 3 shows a general aviation aircraft selection available in the INM, ranging from light turbofan (Citation) to turbojet aircraft (Lear 25). The composite jet is an approximation of the national fleet average.

TABLE 3 Common General Aviation Jet Aircraft in INM Data Base 8

Type	INM Name
Lear 35/TFE-731	GALTF
Lear 25/CJ610	GALTJ
Sabre 75/CF700	GAMTF
Citation/JT15D	GALQFT
Composite GA Jet	COMJET

Often the modeler does not have adequate information to be as specific as the model allows, or he has too much information that needs reducing, or the desired aircraft is still not in the model. He may also be faced with trying to select an aircraft fleet of limited known composition for projecting future noise conditions. In any event, the modeler is faced with a predicament of which aircraft to use in the model. An assumption of representative aircraft must be made.

AIRCRAFT COMPARISONS

In order to gain an understanding of the relative contributions of specific aircraft types and engines to noise contours and to provide a simplistic indication of the sensitivity of the INM to aircraft selection and parameter changes, a graphical analysis of individual noise contours produced by the INM was initiated. By using the INM to produce noise contours for a given DNL and specific number of operations, the contour can be representative of an associated single-event noise exposure level for a particular aircraft. The derivation of this methodology is as follows:

$$DNL = SEL + 10 \log (N_d + 10 N_n) - 49.4 \quad (1)$$

$$SEL = DNL - 10 \log (N_d + 10 N_n) + 49.4 \quad (2)$$

where

- DNL = average day-night noise level,
- SEL = sound exposure level,
- N_d = number of day operations (7 a.m. to 10 p.m.), and
- N_n = number of night operations (10 p.m. to 7 a.m.).

Assuming $N_d = 10$ and $N_n = 0$, the following values are obtained:

SEL	DNL
90	50.6
95	55.6
100	60.6
105	65.6

An SEL of 95 (DNL = 55.6) was selected as the level for comparison of all aircraft and parameter modifications in this analysis. DNL contours of 55.6 were prepared by the INM for 10 approaches and 10 departures for each aircraft in Tables 1-3. In addition, contours were prepared for other aircraft in the INM for comparison. Each contour was plotted at a similar scale with approaches from the left and departures to the right. Figures 1 through 9 show the contours of various groups of aircraft along with their INM name and calculated contour area in square miles.

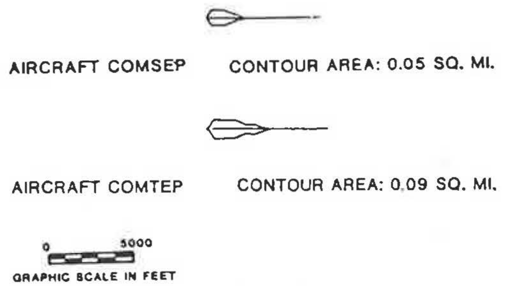

FIGURE 1 General aviation propeller aircraft noise contours.

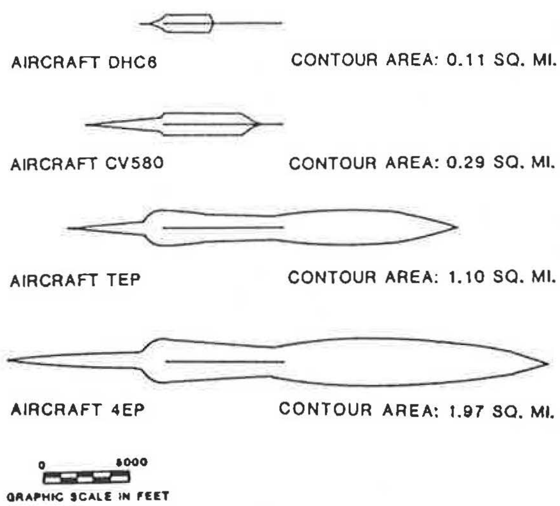

FIGURE 2 Turboprop and large-propeller aircraft noise contours.

Figure 1 shows the relative levels of the single-engine (COMSEP) and twin-engine (COMTEP) general aviation propeller aircraft used in the model. As expected, these were the smallest of those studied. Very little approach noise is noted. In Figure 2, larger propeller and turboprop aircraft are shown. The DHC6 is a small turboprop with short-take-off-and-landing (STOL) performance abilities. This is made evident by the short departure contour. Although not characteristic of the small commuter turboprop fleet, it is the only selection of this type in the data base. The CV580 is a large twin-engine turboprop. Large twin-engine and four-engine propeller aircraft are shown as the TEP and 4EP contours. These represent the old DC-3 and DC-6,7, respectively, and are relatively loud.

A significant difference in contours among general aviation jets is shown in Figure 3. The smallest is the GALQTF, a light, quiet turbofan jet represented by the Cessna Citation. The largest is the GALTJ, or light turbojet, shown as the Lear 25. The COMJET, or composite general aviation jet, is available for modeling of unknown fleet operations. It appears to be dominated by turbojet contributions. The last two contours are much larger than the two-engine commercial jet (DC-9, 737) contours. Because of this, the modeler should be careful in identifying actual general aviation jet activity, particularly if it is a significant portion of the overall operations.

Figure 4 shows the commercial two-engine DC-9 narrow-body aircraft noise contours. The DC-910 and the DC-930 are the untreated and noncomplying (with federal noise regulations) aircraft. Specific models of these aircraft have been issued exemptions and can still operate in the United States. The DC9Q7 and DC9Q9 are the acoustically treated quiet nacelle versions of the DC-910 and DC-930, respectively. The significant difference of the treatment is obvious for approach noise, but there is very little dif-

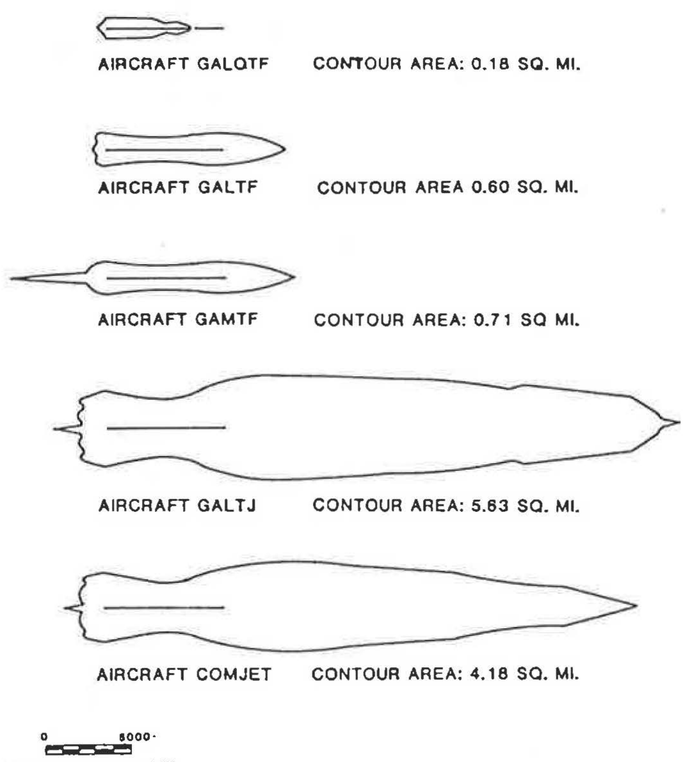

FIGURE 3 General aviation jet aircraft noise contours.

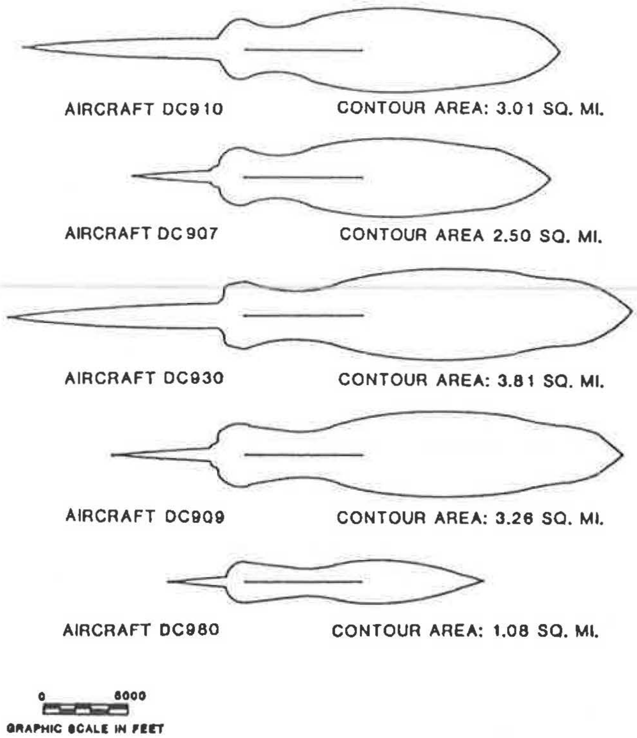

FIGURE 4 DC-9 aircraft noise contours.

ference in departure noise. Also shown is the DC-980 or MD-80. This is the new version of the DC-9 with newer higher-bypass-ratio engines. Significant noise reduction for departures as well as approaches is noted. Improved performance characteristics add to the noise reduction.

Other two-engine, narrow-body aircraft contours are shown in Figure 5. The BAC111, often considered to be one of the noisiest aircraft, has the longest approach noise contour. The 737 and 737QN contours are quite similar to those of the DC-930 and DC-9Q9. Still, there are specific differences among all of the two-engine, narrow-body aircraft.

The differences between the 727-100 and 727-200 three-engine, narrow-body aircraft are shown in Figure 6. All these aircraft are required to comply with federal noise regulations. The 727Q7 contour shows the reduction achieved by quiet nacelle addition to the 727-100. Again, there is more reduction in approach noise. The 727Q15 contour represents the 727-200 with the more powerful but treated nacelle engines. The contour is broader and shorter, depicting more power along with higher performance.

Three-engine, wide-body aircraft contours are shown in Figure 7. These aircraft have high-bypass-ratio engines and produce much less noise than the older low-bypass-ratio engines found on the DC-9, 737, and 727. These aircraft either meet or approach the most stringent federal noise requirements (FAR Part 36, Stage 3). There is very little difference between the DC-1030 and L1011 contours.

Figure 8 shows the contours for three of the new-generation two-engine, high-bypass-ratio aircraft. The contours are significantly smaller than those produced by low-bypass-ratio aircraft. The continued introduction of these and other new-generation aircraft into the fleet will eventually contribute to the reduction of aircraft noise impacts.

The effect of acoustically treating the engines against completing re-engining of an aircraft is shown in Figure 9. The four-engine, narrow-body DC8QN represents the low-bypass-ratio engine with quiet nacelle treatment. The DC8CFM is the same aircraft with new high-bypass-ratio engines. The beneficial effects of noise reduction are obvious, and performance and fuel efficiency are increased as well.

STAGE LENGTH COMPARISONS

The effect of weight on departure performance of an aircraft may be noticed in the noise contour shapes. An INM user specifies the weight of an aircraft departure indirectly by assigning a stage length or first-destination distance category for each flight. Profiles for different stage lengths have different climb performance and thrust levels. Each stage length is associated with a take-off weight representative of a typical load factor and fuel required

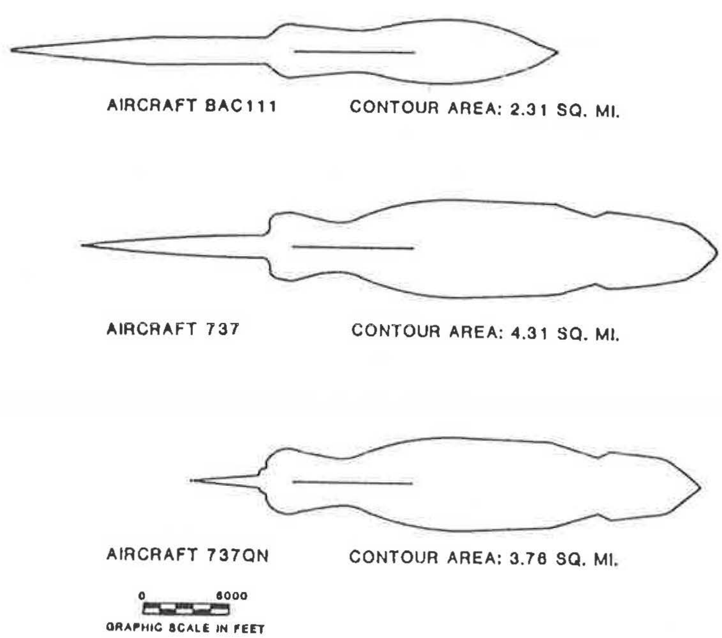

FIGURE 5 BAC111 and B727 aircraft noise contours.

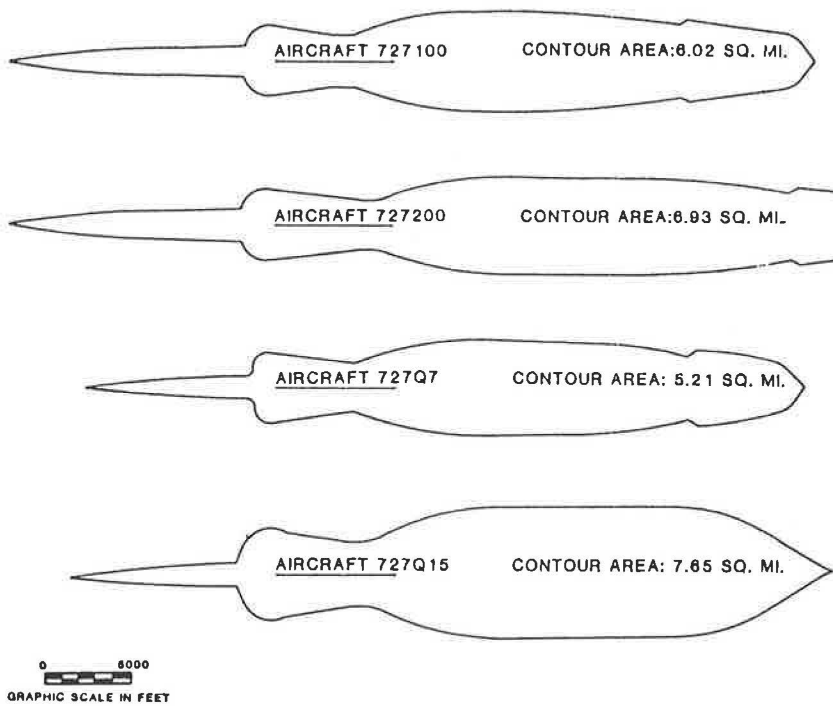

FIGURE 6 B727 aircraft noise contours.

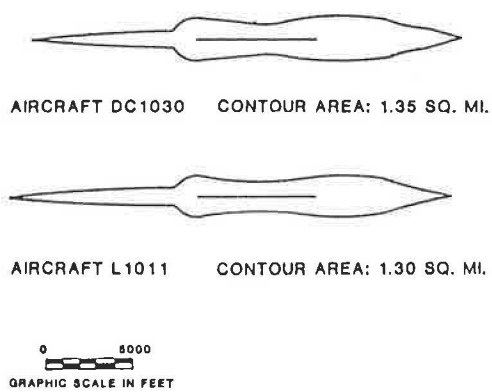

FIGURE 7 DC-10 and L1011 aircraft noise contours.

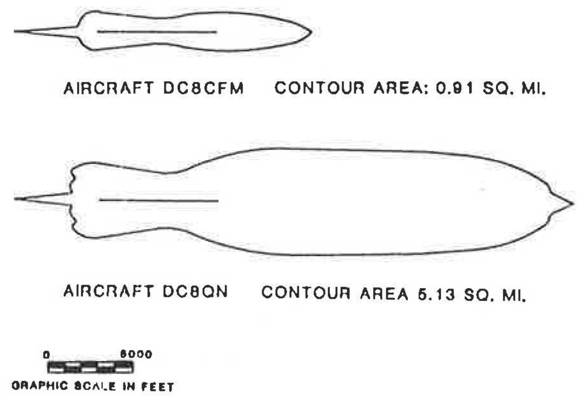

FIGURE 9 DC-8 aircraft noise contours.

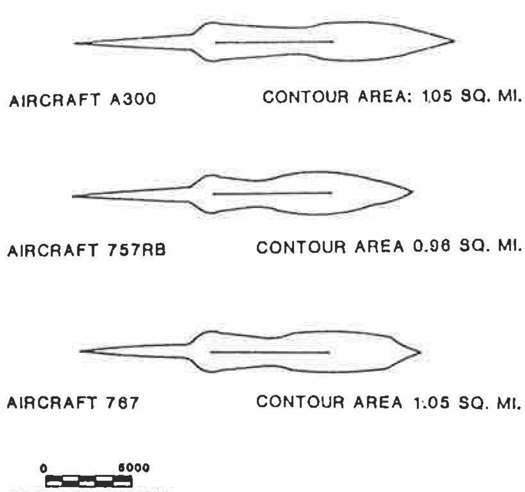

FIGURE 8 A300-B757-B767 aircraft noise contours.

for such a flight. The following are the ranges of the aircraft stage lengths in the INM:

Stage Length	Distance (nautical mi)
1	0-500
2	500-1,000
3	1,000-1,500
4	1,500-2,500
5	2,500-3,500
6	3,500-4,500
7	4,500 and greater

All of the previous contours shown in Figures 1-9 were modeled with aircraft departures of stage length 1. For comparison purposes, the DC-9, 727, 767, and L1011 were modeled by assigning different stage lengths. The effects are shown in the contours in Figures 10-13.

The DC-9 is usually used for short-haul operations (less than 1,000 nautical mi). Figure 10 shows the contours for the typical stage lengths of the

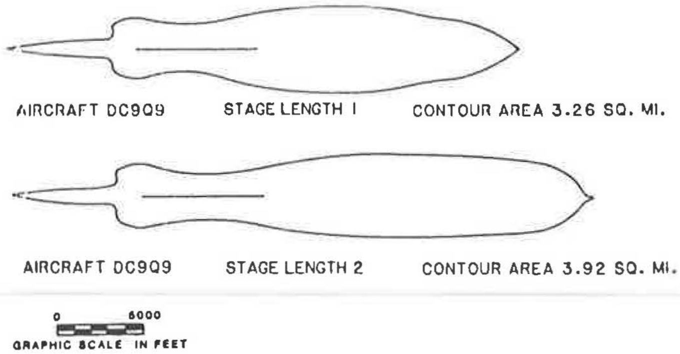

FIGURE 10 DC-9 stage length comparison.

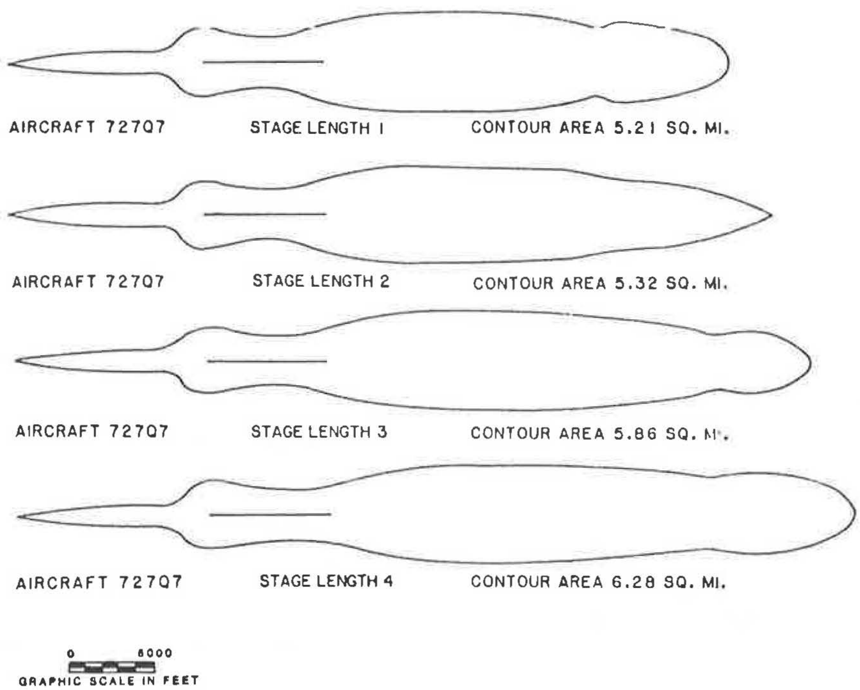

FIGURE 11 B727 stage length comparison.

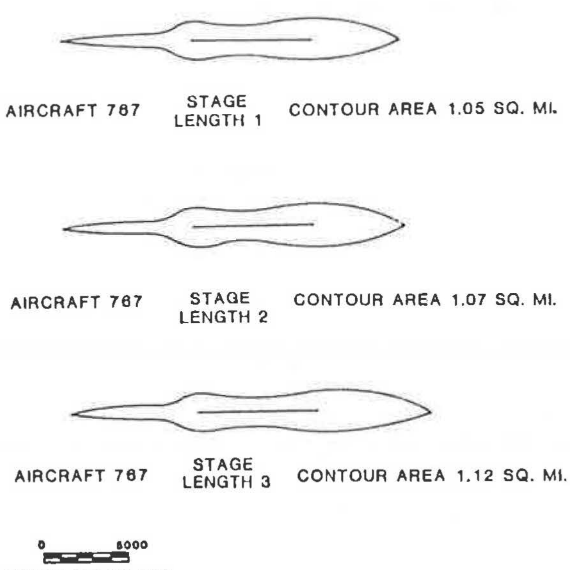

FIGURE 12 B767 stage length comparison.

DC9Q9. Stage length has no effect on approach noise but does show some change on departure contours. The 727, a workhorse for short- to medium-haul flights, shows increasing noise exposure with increasing stage length, as shown in Figure 11. The higher-performance 767 aircraft shows less noise and less variation as a result of stage-length changes, as shown in Figure 12. Finally, the contours of Figure 13 for a long-haul aircraft, the L1011, show moderate change in shape and area from stage lengths 1 to 3 to 6.

ALTITUDE AND TEMPERATURE COMPARISON

The INM provides the user with the opportunity to select the altitude or elevation and temperature at the airport to be modeled. The contours in Figures 1-13 were generated for an airfield with an elevation of 50 ft and temperature of 80°F. To see the effect of changes in these parameters, the 727Q7 was modeled at runway elevations of 50, 1,000, and 5,000 ft. Also, the 727Q7 was modeled with an elevation of 50 ft and changes in temperature from 80° to 50° to 20°F. The results are shown in Figures 14 and 15.

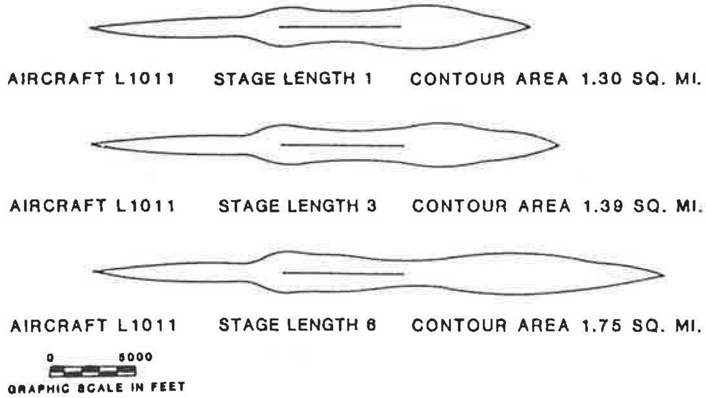

FIGURE 13 L1011 stage length comparison.

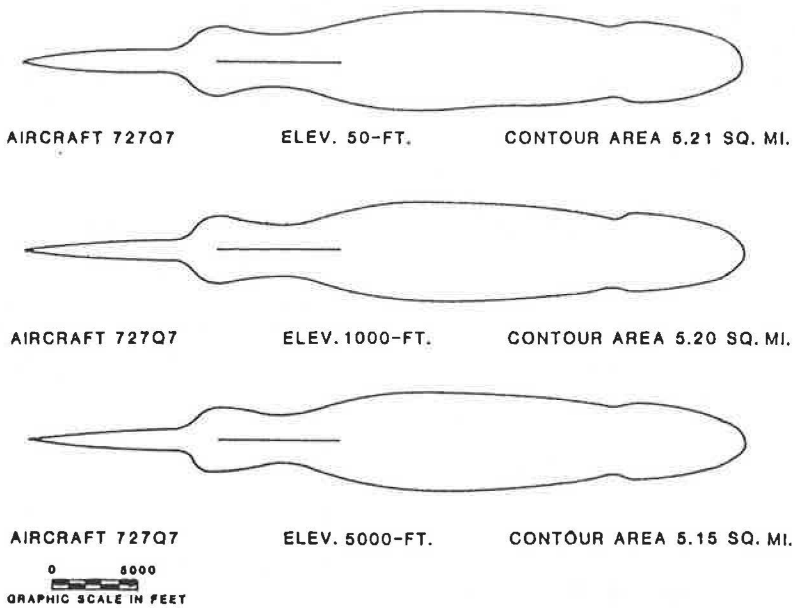

FIGURE 14 B727 airport elevation comparison.

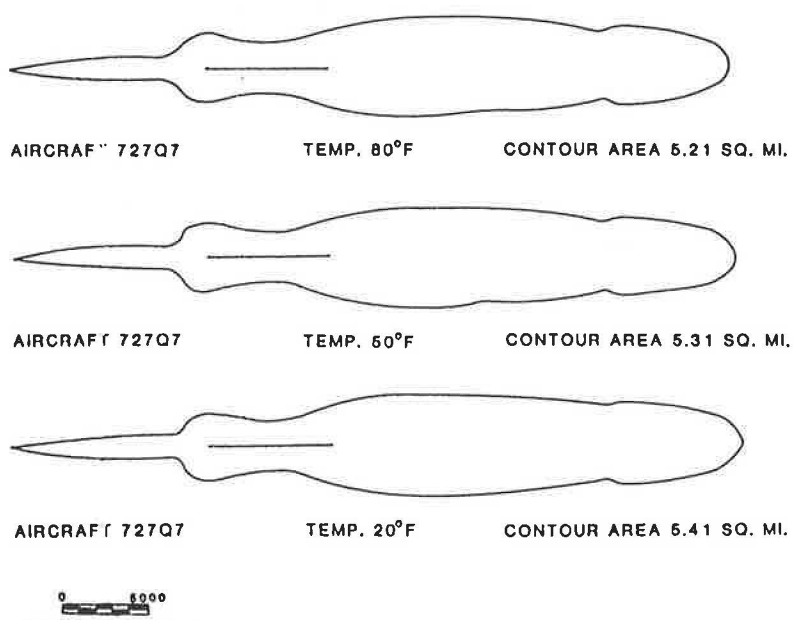

FIGURE 15 B727 airport temperature comparison.

Visually, there appears to be no major difference for the contours with changes in either elevation or temperature. Contour areas show a slight decrease in area with increasing altitude and increasing temperature. This is contradictory to the idea that with increasing elevation and temperature, aircraft performance drops and the noise is spread out longer on departure. Further investigation reveals that the INM uses the elevation and temperature parameters for adjusting aircraft velocity (referenced at 160 knots). At higher elevations and temperatures, an aircraft must achieve greater ground speed for flight. With this higher velocity, there would be a shorter noise exposure time for a fly-over and a corresponding reduction in contour size. This would appear to agree with the contours shown in Figures 14 and 15.

However, the INM does not appear to adjust the departure profile for changes in elevation and temperature. For example, at higher elevations, additional runway roll would be needed to achieve the necessary airspeed. With this, an aircraft would be at a lower altitude over a given point down range. The profile would be extended and increased noise should occur. Whether or not this effect is accounted for and offset by the velocity correction is not clear. Preliminary indications are that it may be necessary for the user to modify departure profiles by extending runway roll distance for a particular elevation and temperature or select alternative stage lengths that provide desired profiles.

OTHER COMPARISONS

There are several other areas in which the sensitivity of the INM could be determined. However, this type of analysis would require the user to provide his own information and data on particular aircraft noise levels and operational characteristics. The foregoing analysis focused only on those parameters that are immediately available to the user in a "default" form.

Several studies have been conducted aimed at validating particular components of the INM and its data base (4-6). The components included comparisons of INM flight profiles and noise curves with observed values. Recommendations for corrections to the model were made in those studies.

CONCLUSIONS

This paper has provided a review and insight into the current airport noise analysis process and the problems facing the modeler. The extensive data base and the flexibility for user input make the INM a valuable state-of-the-art tool for today's noise compatibility studies as well as environmental impact assessments. Because critical decisions are being made based on information derived from the INM, users must seriously consider all assumptions made in a modeling effort. The simple sensitivity analysis done in this effort gives an indication of the latitude available for some assumptions dealing with aircraft type, stage length, elevation, and temperature.

No recommendations are made in such areas as combining aircraft into groups or stage length selection. Rather, this information may be used as guidance in selecting particular aircraft types or configurations for an analysis. The study does point to the need to adequately assess the sensitivity of the INM to changes in airport elevation and temperature. Specifically, the effect of these parameters on the aircraft departure profiles needs to be clarified.

In addition, a more intensive and complete investigation into the sensitivity of the INM to variations of all input variables should be conducted. The identity of the variables and their ranges that have the most effect on noise levels should be determined. The analysis should consider not only the absolute effects, but how these effects would materialize in typical model usage.

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