N-96-01
II-A-258

WYLE LABORATORIES

REPORT

WYLE RESEARCH REPORT

WCR 75-2

Community Noise Countermeasures Cost-Effectiveness Analysis

By

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320 New Center Building
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July 1975

N-96-01
II-A-258

ACKNOWLEDGMENTS

The authors wish to acknowledge the able help and support they have received from:

Dr. Leonard Merewitz, University of California at Berkeley, in the area of economics;

Charles Coughlin and Gary E. Mange in the area of computer modeling;

Patrick K. Glenn in the area of demographic and geographic data collection and processing;

and Donald B. Pies for literature surveys and general support.

Furthermore, the encouraging support from Dr. J. Hayden Boyd, MVMA, and the many helpful suggestions from the Community Noise Committee of MVMA are gratefully acknowledged.

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CHAPTER 1
INTRODUCTORY SUMMARY*

1.1 INTRODUCTION

The objective of this study is to provide supporting information for use in formulating motor vehicle and highway noise policies within an overall national policy of community noise abatement. In the course of the research work, a comprehensive community noise exposure model capable of evaluating and optimizing** noise reduction countermeasures, especially as related to ground transportation noise sources, has been developed. The model has been evaluated for a defined future time period (1978), and refined on an actual experimental city (Spokane, Washington) which has been selected as a typical U.S. city from a noise exposure standpoint. Hence, results obtained in the analysis conducted for Spokane are applicable to a broad category of U.S. cities, with certain specific cautions, which are further defined later.

The development of the noise exposure model involves studies into the diverse areas of individual noise source level prediction, technical and economic analyses of feasible noise reduction countermeasures that could be applied to these sources, analysis of human reaction to total environmental noise exposure, and the integration of these components into a comprehensive noise exposure prediction and countermeasure effectiveness analysis model. A schematic diagram of the function performed by the noise exposure model is illustrated in Figure 1.1-1. The modeling process may be summarized as follows:

a. The city or city segment to be analyzed is first divided into noise exposure zones or cells. Each cell is selected such as to be acoustically homogeneous, that is, the propagation of noise within a specific cell is a function of the cell land use and hence, the cell should contain only one dominant land use. In other words, the city is subdivided according to its "acoustic geography."

*All relative and absolute sound levels in dB are A-weighted levels unless otherwise specified.

**In this report, the word "optimization" is understood to really mean "maximization of cost-effectiveness." Similarly, words with the same root "optim..." have analogous meanings.

b. The major sources of environmental noise to be treated in the analysis are defined relative to the cell distribution defined in (a).

c. The level of source activity (traffic flow volume, heavy truck percentage, number of freight train passbys) is then quantified for the time periods of interest: the day and nighttime periods utilized by the Environmental Protection Agency for defining the day-night equivalent sound level L_{dn}.

d. The information obtained in (b) and (c) is combined through a series of pre-established individual source noise prediction models to yield the noise levels from each source which are then combined to yield the composite total exposure at each cell for each time period of interest. In the analysis conducted, this overall exposure is quantified in terms of two metrics: mean energy equivalent level (L_{eq}) and Noise Pollution Level (L_{NP}).

e. With the total noise exposure at each cell so defined, transfer functions are applied which correlate the noise exposure defined in (d) to the average percentage of persons in that cell at that time who will respond adversely (or loosely, will be "annoyed") to this exposure as indicated schematically in Figure 1.1-1, column f.

f. Given the percentage of people responding adversely in each cell to the quantified level of noise exposure, the actual population in each cell is considered next.

g. The total number of persons "impacted" (i.e., responding adversely) at each cell location for each time period is obtained by combining (e) and (f). A summation of the total number of persons impacted by time period and location (i.e., a spatial and temporal integration) yields the "Noise Impact Index" which becomes a relative measure of the

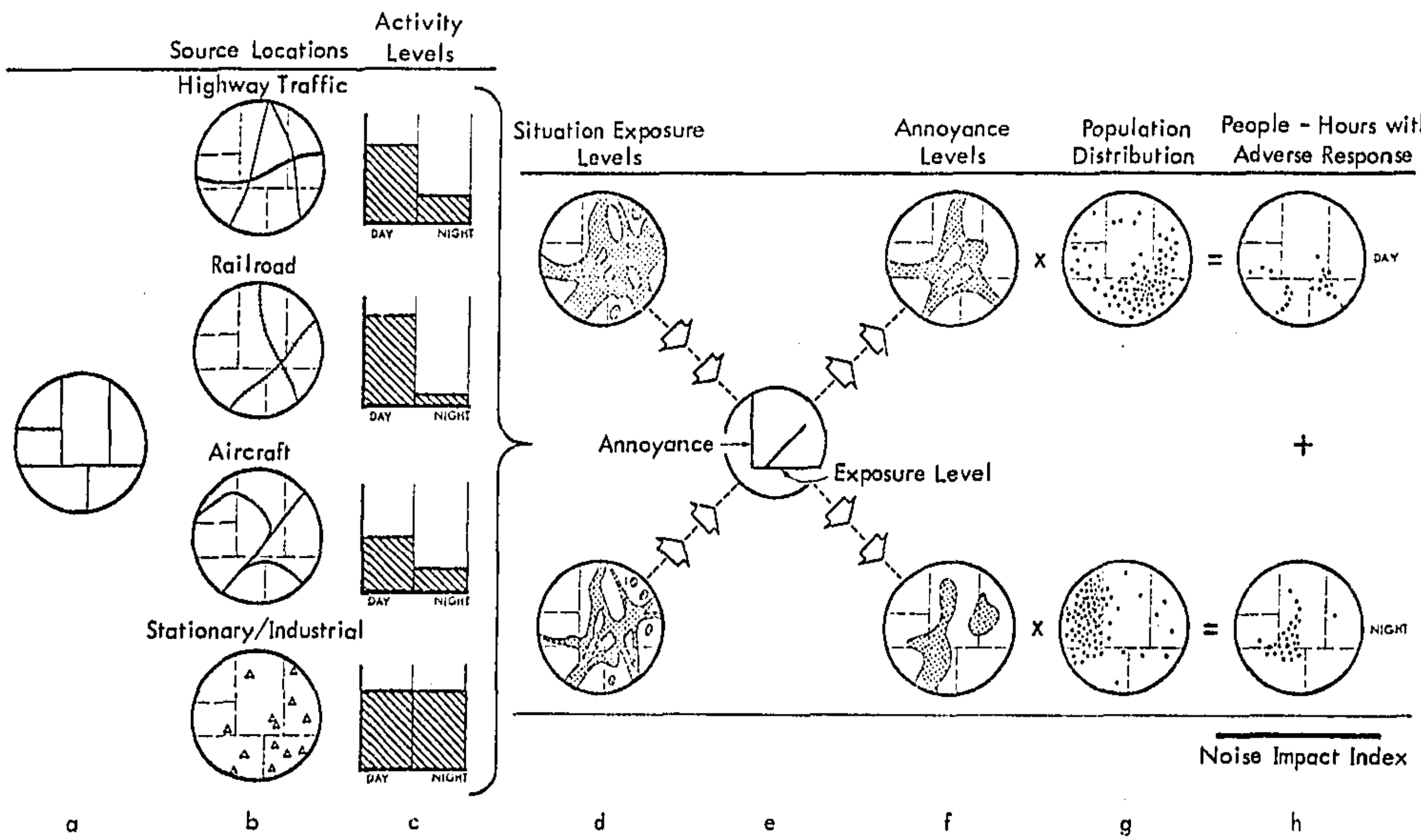

Figure 1.1-1. Schematic of Community Noise Exposure Model Leading to Noise Impact Index

degree of success of the various noise reduction programs in terms of application of various scenarios of noise countermeasures to the community. It should be observed that the present state-of-the-art in prediction of human response to environmental noise exposure is wrought with a number of uncertainties such as to preclude placing substantial significance upon the absolute values of the NII so obtained. However, as will be shown later, this does not detract from the validity of its use as a reliable relative indication of countermeasure effectiveness.

In the following sections of this introductory summary, the various supporting segments of the modeling procedure are summarized with the results of the analysis on optimization of community noise countermeasures for Spokane, Washington, being presented in Section 1.8.

The detailed background, analysis methods, and results of the study are then presented in the subsequent chapters in the same sequence as in this introductory summary. Additional supporting details are covered in the appendices.

1.2 NOISE METRICS

In Chapter 2, a study of the relative merits of various noise rating scales (or "noise metrics") has been conducted. Scales based on the A-weighted level are the most common at this time. Although A-weighting may not correlate in the best manner with human response, it is selected because of its widespread use and because instrumentation with A-weighting networks is readily available.

In order to quantify the noise exposure from a single event, from a stream of single events, or from a continuous on-going source, the energy mean equivalent level (L_{eq}) has been selected. It is given preference over other noise-metrics because of its attractive mathematical simplicity and because it can be measured easily. The combination of equivalent levels from different sources can be performed in a straightforward manner. It has also been found that L_{eq} correlates reasonably well with human response. It is therefore used in the greater portion of the present study.

There is evidence that the Noise Pollution Level (L_{NP}) may show a better correlation with human response than L_{eq} because it takes into account not only the total noise energy a listener is exposed to, but also the often so annoying variability of noise levels. However, the computational process of obtaining L_{NP} is much more complicated: the complete statistical distribution function of noise levels must be known. A supplementary study using L_{NP} as the basic noise metric has been conducted.

1.3 TRANSFER FUNCTIONS

As mentioned in paragraph (e) of Section 1.1, a transfer function gives the relationship between noise exposure and adverse human response to this noise exposure. The term "adverse response" is used instead of the word "annoyance" because it is desired to include not only irritation caused due to interference with activities, but also the effect of noise on health (in particular the hearing mechanism) of which a person may not even be aware.

A transfer function consists of three branches:

- At very low noise levels (below the "lower criterion level"), it is assumed that nobody responds;
- At very high noise levels (above the "upper criterion level"), it is assumed that everybody responds adversely;
- The branch between the lower and upper Criterion Levels defines the relationship between the percentage of adversely responding people and the noise levels which fall between the Criterion Levels.

The Criterion Levels are generally obtained by an analysis in four steps:

- Determine the land use and the time of day; define people's activities;
- Define upper and lower Criterion Levels associated with each activity from data published in the literature (activities involving voluntarily generated noise are grouped into a separate category and are assigned higher Criterion Levels);
- Analyze the percentage of time spent in each activity;
- Sum the Criterion Levels in each activity on an equal energy basis.

The above procedure results in Criterion Levels applicable indoors. The outdoor Criterion Levels are arrived at by adding the average noise reduction of buildings. Table 1.3-1 shows the resulting outdoor Criterion Levels utilized for this study.

Table 1.3-1

Outdoor Criterion Levels
LC_ℓ = Lower Criterion Level, LC_u = Upper Criterion Level

Land Use	LC_ℓ, dB		LC_u, dB	
	Day	Night	Day	Night
Residential, Single-Family Dwellings	50	42	85	77
Residential, Multiunit Dwellings	55	42	90	77
Commercial and Industrial	55	55	90	90
Schools	50	-	85	-
Hotels and Motels	55	50	90	85
Hospitals and Nursing Homes	53	50	88	85

For the greater portion of this study, the shape of the transfer function between the Criterion Levels is taken to be a straight line. There is evidence, however, that a nonlinear s-shaped transfer function is a better approximation to the way people respond to noise on a long-term basis. The effects of nonlinear relationships of this kind on the final cost-effectiveness analysis are also explored in this study.

1.4 QUANTIFICATION OF COMMUNITY NOISE

The urban outdoor noise environment is generally dominated by transportation noise. For the specific purposes of the noise countermeasure effectiveness analysis of this report, the following sources are considered: automobiles and trucks (each at low and high speeds), city buses, railroads, and aircraft.

The noise from motor vehicles is estimated using a Wyle-developed highway noise simulation program which computes the equivalent level L_{eq} by adding the acoustic energy from all vehicles and averaging over time.

High-speed roadways are treated as two separate noise sources in order to single out the tire noise component for which there exists only very little noise reduction potential for the foreseeable future.

Motor vehicles are generally broken down into only two categories with significantly different noise properties: automobiles and trucks. In the central business district, transit buses are also considered an important separate noise source.

Railroad switching yards and stations are considered parts of industrial areas. Only on-line operations are considered as separate noise sources. Because of their very different characteristics, the noises from locomotives and railway cars are treated separately.

Aircraft noise exposure and countermeasure analysis are conducted through use of a Wyle/DOT computer model which computes Noise Exposure Forecast values for noise exposure near airports. These NEF values are then converted into equivalent A-weighted noise levels to be compatible with the remainder of the analysis. This model takes into account:

- The geography and geometry of the airport and of the approach and departure paths,

- The operational characteristics of each aircraft type together with its noise output.

In order to complete the quantification of community noise, one needs to know the sound propagation losses. In an urban area where the sound propagation path is not flat like over open terrain, the prediction of propagation losses becomes a difficult problem. A conceptual model has been developed to handle the wide range of situations which can occur, i.e., a single isolated barrier or a cluster of buildings.

For the supplementary study using the Noise Pollution Level L_{NP}, a different approach to quantification of community noise has to be used. The general method consists of obtaining first the distribution of noise levels from each source, then combining these to form the distribution from all sources.

In order to obtain the cumulative distribution function of noise levels from road traffic, a published mathematical model is used. The following input variables are required for each class of vehicles (i.e., automobiles, trucks, etc.):

- The number of vehicles per unit distance of roadway,
- A reference noise level measured at a standard distance.

In addition, the perpendicular distance of the observer from the roadway must be known.

The distribution of noise levels from railroad operations is obtained from an abstracted time history of train passbys.

The distribution of noise levels from aircraft operations is obtained by considering the noise level time history generated by a moving dipole oriented at 45 degrees to the direction of travel and moving at the speed of the aircraft. The dipole approximates the directivity pattern of the jet noise.

The cumulative distribution functions from single events or from a class of sources are combined by a published method which utilizes a semi-empirical formula for combining two noise source distributions at a time. If there are many distributions, the formula has to be applied repeatedly in succession for each pair of sources or groups of sources.

Both the energy equivalent level L_{eq} and the standard deviation σ are calculated from the final combined distribution. The Noise Pollution Level then follows from the formula first proposed by D.W. Robinson:

$$L_{NP} = L_{eq} + 2.56\sigma$$

1.5 NOISE COUNTERMEASURES AND THEIR COSTS

The technical feasibility of accomplishing varying degrees of noise reduction for the time period 1973 to 1978 is analyzed. A distinction is made between source countermeasures, and countermeasures associated with the sound path and the receivers.

The dominant noise sources, which are oriented toward transportation, are:

- Heavy trucks (over 10,000 lbs gross weight)
- Automobiles and light trucks
- City buses in the central business district only
- On-line freight and passenger railroad operations
- Commercial aircraft

The general approach to the analysis includes a definition of the major noise producing subcomponents for each source and the extent to which feasible noise reductions can be accomplished either through modification of new products or retrofit of existing vehicles. Different modes of operation are also considered, and the different degrees of noise reduction are predicted for the various operating modes of each type of source. Where appropriate, the methods of noise reduction consider not only physical source modifications, but operational modifications as well affecting the individual and the composite fleet.

In the area of path and receiver treatments, the following subjects are considered:

- Rerouting of moving sources
- Construction of noise barriers
- Improvement of outdoor to indoor sound insulation of buildings
- Receiver relocation out of the proximity of a source

The actual sources analyzed in this study and their corresponding noise reduction countermeasures, along with a list of sources not included, are summarized in

Table 1.5-1. In general, this study focuses on surface transportation and commercial and military aviation noise sources. These are the noise sources that have been consistently identified in most community noise surveys as the dominant sources of disturbance with outdoor noise. The noise countermeasures selected for evaluation are considered the dominant ones for general abatement of community noise levels. Even here, however, exceptions occur in that operational control of such sources as excessive horn honking or squealing brakes is not considered. The other major exclusion from this study might be considered the self-generated noise exposure in and around one's own home. Thisis not necessarily intrusive on one's own environment, but can, in some circumstances, contribute to noise intrusion for neighbors.

For all the above countermeasures, information on costs has been gathered from vehicle manufacturers and operators, and from data available in the literature, as well as from previous Wyle experience. Information available as of September 1974 has been included. Insufficient data were available on the costs of installing noise reducing hardware on already existing motor vehicles ("retrofit"). In general, it is assumed that the total retrofit costs (parts + labor) are equal to the incremental retail costs of manufacturing a new motor vehicle with the same noise reduction modification. In order to explore the sensitivity of the results to this assumption, a substudy is conducted in which the motor vehicle retrofit costs are tripled and the effect of this on the final results is investigated (see Section 1.8.6).

1.5.1 Motor Vehicles

Heavy-duty trucks are manufactured in many different configurations, so that it cannot be said that any one source dominates. Although significant advances have been made in reducing exhaust noise, it is still a major source. The incorporation of adequate mufflers is relatively simple both at the manufacturing level and as a retrofit in the field. Sometimes there exist problems of installation clearances. Engine mechanical noise can be reduced by installing partial or complete enclosures, generally resulting in somewhat less noise reduction than in the case of the exhaust, but costing more. A great deal of effort is currently going into noise reduction from the engine

Table 1.5-1

Summary of Sources and Noise Reduction Countermeasures Considered for This Study. Shaded Areas: "Not Applicable."

Noise Source			Countermeasures								
			Source Control						Path/Receiver Control		
			Design		Operation						
Type	Not Included	No C.M.(5)	New Product	Retrofit	Roadway	Mode (Speed, Pwr, etc.)	Frequency (Curfew)(2)	Rerouting	Barriers	Bldg Noise Treatment	Land Acquis(8) and Relocation
Autos - Engine/Exhaust			←(1)→						x	x	x
- Tire Noise		x							x	x	x
Trucks - Engine/Exhaust			< 35 mph only(2)						x	x	x
- Tire Noise			> 35 mph only(3)						x	x	x
Buses - Engine/Exhaust			x	x						x(7)	(9)
- Tire Noise	x										
Motorcycles	x										
Com'l A/C - Flight				x		x	x	x		x	x
- Ground Runup	x										
Gen'l Av A/C - Flight	x										
Military A/C - Flight		x								x	x
- Ground Runup	x										
Passenger/Freight Train				x(4)					x	x	x
Railroad Yard	x										
Rapid Transit	x(6)										
Construction Noise	x										
Industrial Plants	x										
Home Appliances - Outdoor	x										
- Indoor	x										
People	x										
Pets (Barking Dogs)	x										
Natural Sources (Wind)	x										

Notes

(1) Automobile engine/exhaust noise reduction applied at all speeds.
(2) Truck engine/exhaust noise reduction applied at low road speeds only on the basis that truck engine speed is approximately constant.
(3) Truck tire noise and noise reduction considered only at high (≥35 mph) road speeds.
(4) Retrofit of diesel-electric locomotives with engine exhaust mufflers and quieter cooling fans.
(5) No countermeasures (C.M.) applied directly to source.
(6) Not applicable in Spokane.
(7) Commercial building noise reduction treatment in Central Business District only.
(8) Land acquisition costs considered as continuation of building noise reduction cost function. Due to their higher costs, this option was therefore never selected as cost-effective.
(9) Land acquisition costs in Central Business District assumed infinite to preclude this option.

cooling fan, often emphasizing a complete redesign of the cooling system. Some of the promising possibilities are:

- Careful design of the radiator, the fan and its shroud and the pulleys behind the fan;
- Use of a thermatically-controlled demand-type fan clutch; it has been estimated that the fan is actually required only 10 percent of the engine running time so that the fan could be switched off for a great portion of the time the truck is operating in a noise-sensitive area. The costs for changes to the cooling system are somewhere between the ones for exhaust and engine mechanical noise.

High-speed truck tire noise can be reduced on the order of 5 dB by replacing crossbar design tires with rib design tires; however, the costs are unattractive.

It is important to realize that noise level reductions as measured by the SAE standard testing procedures at wide open throttle do not normally translate directly into the same amount of level reduction under actual realistic driving conditions. This study presents analyses aiming at approximate functional relationships between the SAE level reduction and level reduction for various driving modes. It is found that for trucks at low speeds (less than 35 mph), there exists a direct one-to-one relationship. For most other cases (trucks at high speeds [greater than 35 mph], automobiles at all speeds), the actual noise level reduction is less than the one demonstrated by the SAE test. Only for the acceleration driving mode of automobiles may the direct one-to-one relationship be assumed between actual and SAE test levels.

The unreduced noise levels from cruise mode are determined from previous measurements (published in the literature and from Wyle Laboratories files). For deceleration, it is assumed that the noise level is equal to that of the cruise mode at the speed from which deceleration occurs. It is further assumed that idle mode noise levels are unaffected by noise reduction measures.

Automobile exhaust noise reduction can be effected at a relatively small incremental cost at the manufacturing level. Fan noise may be minimized by the use of improved design flex-bladed fans or by the incorporation of heat-sensing demand-type fan clutches. It is not anticipated that high-speed automobile tire noise can be reduced significantly by the year 1978.

Commercial buses are assumed to be an important separate noise source only in the central business district. There, it is assumed that half of the time is spent accelerating and half of the time is spent decelerating. Most of the buses are diesel buses. They share many common power train elements and performance features with heavy trucks, so that most of the noise reduction concepts for heavy trucks are applicable.

1.5.2 Railroad Sources

The two predominant noise sources are: the diesel-electric locomotives and the passenger or freight cars. Locomotive noise is largely dominated by low-frequency exhaust noise. Other sources are fans cooling both engine and large resistor banks (the latter are used during dynamic braking), and the turbocharger producing a whine. A reduction of locomotive noise of approximately 6 dB could be obtained by equipping the existing fleet of locomotives with mufflers and making some changes to the fans.

While locomotive noise is largely independent of speed, the noise from rail cars increases approximately 6 dB for each doubling of train velocity. The magnitude of the noise depends heavily on the conditions of the wheels and the track and on the type of car suspension. Freight cars produce the highest noise levels due to their high unsprung rolling stock mass, whereas passenger cars are typically 5 to 10 dB quieter. It is not anticipated that rail car noise can be reduced significantly by 1978, so that only locomotive retrofit countermeasures are incorporated in the present effort.

1.5.3 Aircraft Sources

Only the noise from commercial and military jet aircraft is considered in this study. Only commercial aircraft are considered for noise reduction measures. Recent work by Wyle, DOT, and EPA have provided an adequate data base for the evaluation of cost-effectiveness of reducing the aircraft noise portion of community noise using available technology for aircraft noise reduction. The following four noise countermeasures have been selected for the present analysis:

- Two-segment approach
- Aircraft rerouting by means of modified ground flight tracks to avoid populated areas
- Quiet nacelle retrofit (SAM) of existing commercial aircraft
- Implementation of a night flight curfew

Other countermeasures that are a priori estimated not as likely to be cost-effective for inclusion in this study are: retrofitting aircraft with quieter design engine fans (REFAN) in combination with the quiet nacelle treatment (SAM), operational restrictions in the form of eliminating noisy aircraft operations on certain runways or banning noisy aircraft from the airport, operational modifications such as displaced runway threshold for approach and takeoff where safety considerations are satisfied, power cutback departures, and higher minimum altitude.

1.5.4 Path-Receiver Countermeasures

For residential dwellings, an approximate noise reduction improvement of 7 dB can be obtained by minor dwelling modifications such as adequate weather stripping around doors, use of snug fitting doors and windows, elimination of louvered windows, and treatment of exterior vents. Moderate dwelling modifications can give noise reduction improvement of the order of 9 dB which would include the incorporation of double-glazed or sealed windows (often necessitating air conditioning), increasing the amount of sound absorption material in the attic space, and, where required, finishing of crawl spaces with gypsum board. Approximate sound insulation improvements of 17 dB can be obtained by major modifications consisting of all items mentioned previously plus structural improvements to walls and roofs as well as double-entry doors. The costs of improved noise insulation per square-foot of floor area range from $2.50 for minor modifications to about $10 for major modifications.

For commercial buildings and schools, the sound insulation cost per square foot shows about the same trends as the one for residential dwellings.

Barriers have been employed mainly to counter the propagation of noise from traffic arterials and freeways. Experience has shown that a reduction of 5 to 10 dB is easily obtained, whereas 15 dB occurs rarely. The most effective barrier design appears to be an earthen mound topped by a concrete or brick wall with a sound absorbing surface on the noise exposed side.

When everything else fails, the sound receivers can be moved to quieter areas. In this study, the following two assumptions are made so that this countermeasure can be considered:

- The loss of value of the land is limited only to the loss of the value of the property improvements at the time of acquisition
- The displaced homeowner or renter receives compensation as determined by the national average paid under court judgments.

1.6 PRESENT VALUE ANALYSIS OF NOISE REDUCTION COSTS

The functional relationships between the amount of noise reduction due to each countermeasure and the cost associated with effecting this noise reduction are established. Due to the large number of variables influencing costs, only a range of costs can be given. Three cost functions are identified: low, average, and high.

In order to put costs of all countermeasures on an equal footing, present value analysis is employed: all present and future costs are referred to the "present" (1973). A discount rate of 10 percent is used. All costs are developed to apply to the City of Spokane, Washington, the model city selected for this study (see Section 1.7). For countermeasures involving noise control of sources which are not unique to Spokane (i.e., transportation vehicles), costs are allocated to Spokane on the basis of local usage and population. In all cases, "present value" costs account for initial investment costs, future recurring costs on the first unit, as well as future costs of replacement (so-called cycle costs), where appropriate. The cost data represents the best available information as of September 1974.

1.6.1 Automobiles

Four cases of noise countermeasure scenarios involving different degrees of noise reduction measures are considered. The increased acquisition costs for new production units and the costs for retrofitting the existing automobile fleet are determined. It turns out that for the medium cost function, overall L_{eq} reductions for 1978 at low speed ranging from 1.5 to 3.5 dB are associated with present value costs ranging from 4 to 23 million 1973 dollars. At high speeds, an L_{eq} reduction range from 1 to 2 dB is achieved along with the low-speed reduction.

1.6.2 Heavy Trucks

Seven scenarios of truck noise reduction measures to be taken during the time period 1973 to 1978 are considered involving different degrees of reduction measures. Again, the increased acquisition costs for new trucks and the costs for retrofitting the existing fleet are determined. The retrofit analysis considers not just the vehicle as a whole, but also the components: exhaust, cooling system, engine, and air intake. It also takes into account the present and anticipated age distribution of the truck fleet. For both the new production units and the existing units, increased operating costs due to noise reduction measures are added where appropriate. For the medium cost function, the L_{eq} reduction for 1978 ranges from 3 to 11 dB with an associated present value cost range of zero to about 3 million 1973 dollars. High-speed truck tire noise is considered separately. A reduction of about 5 dB due to use of quieter rib design tires costs between 1.7 to 2.7 million 1973 dollars.

1.6.3 Buses in the Central Business District

Data on noise level reductions and associated costs has been obtained mainly from General Motors. Considering again increased acquisition costs and costs of a 5-year retrofit program for the Spokane bus fleet (45 units in 1973) including increased operating and maintenance costs results in a cost range from zero to 375,000 1973 dollars for an L_{eq} noise reduction range of 0 to 8 dB.

1.6.4 On-Line Railroads

Only locomotive noise reduction is considered. Since at present, locomotives and rail cars contribute approximately equally to the noise energy emitted from a train, noise reduction of only one of these two contributors results in an overall reduction of, at most, 3 dB. Other countermeasures such as wheel and track trueing and grinding, reducing the unsprung mass of freight cars, and curfewing of nighttime operations have been considered, in this study, as either technically or economically unfeasible by 1978.

Zero percent growth of the railroad industry is assumed in this study so that only the present value of costs due to a 5-year retrofit program of the existing locomotive fleet needs to be calculated which includes also the present value of increased operating expenses: a 6 dB locomotive noise reduction costs between $400,000 and $630,000. The overall railroad noise reduction would then be about 2 dB.

1.6.5 Aircraft

Each countermeasure identified in Section 1.5.3 is considered separately. For the implementation of a two-segment approach procedure into Spokane International Airport, it is assumed that:

- Operating costs do not change
- Additional airborne and ground avionic equipment is required with a useful life of 15 years.

The resultant cost is $367,000. Since this is not a source noise reduction measure, but rather an operational procedure, no single dB-value of noise reduction can be given. However, typical reduction in noise levels under the approach path range from 5 to 10 dB.

For the quiet nacelle retrofit of existing aircraft, it is assumed that the retrofit cost occurs only once, since new generation aircraft will replace the retrofitted aircraft upon their retirement. Using an estimate of the total cost to the United States for the retrofit program and factoring this cost by the percentage of commercial jet operations at Spokane International Airport (0.32 percent) yields a cost of 1.85 million 1973 dollars. The approximate noise reductions are:

	Takeoff	Approach
JT3D Equipped Aircraft	1 dB	6 dB
JT8D Equipped Aircraft	6 to 9 dB	9.5 dB

The costs due to rerouting aircraft to avoid densely populated areas are assessed in the form of increased operating costs of equipment, crew and additional fuel, resulting from aircraft having to travel an added distance. Using statistics of what aircraft use Spokane International Airport at what frequency, and statistics of direct operating costs for these aircraft, the rerouting costs are estimated to 5.6 million 1973 dollars.

A night curfew at Spokane International Airport would eliminate only one out of 11 daily flights to Seattle. Using statistics on air travel and on income of air passengers, a calculation of lost manhours assigns a cost of $548,000.

1.6.6 Path-Receiver Treatments

It is assumed that the sound insulation improvement costs for residential and commercial structures recur every 30 years (assumed useful lifetime). Based on the costs per square foot developed above (Section 1.5.4) the present value of the funds that must be spent to achieve a given noise reduction can be calculated from the total floor area in a given cell of the city.

For barriers, a useful life of 50 years is assumed. For barrier heights between 10 and 20 feet, the costs range between $53 and $120 per foot of barrier length.

When properties are acquired as a last resort noise countermeasure, the loss of value is limited to the property improvements. This is a cost which is calculated from property value statistics of the City of Spokane. Another cost is the compensation paid to displaced persons. According to the Uniform Relocation and Real Property Acquisition Policies Act of 1970, homeowners can receive up to $15,000 and tenants up to $4,000 over a 4-year period as compensation for relocation. Based on statistics of actual compensations paid in recent years, the following numbers are used in the present study: $3,035 for homeowners and $2,282 for renters. These are one-time only direct costs.

1.7 SELECTION OF EXPERIMENTAL CITY

In this study, the community noise model with its cost-effectiveness analysis is applied to a real city. If a hypothetical city were chosen, there would always be doubts as to whether or not the results apply to any given physical community. Also, if there is additional detail required, it may not be available from the statistics used to construct a hypothetical city. Detailed data is always available from a real community.

The following criteria were applied during the city selection:

- The city must be a self-contained urban area surrounded by rural land;
- The population should be between 10 and 200 thousand people with a density between 1500 and 6000 persons per square mile;
- There should be an airport with scheduled jet traffic within 10 miles of the city's center;
- A freeway system should exist and rail lines should pass through town;
- There should be an average amount of manufacturing and motor freight activity;
- There should be an average amount of automobile ownership and usage;
- The mean January and July temperatures should be near the national average;
- Community planning information should be readily available.

Based on these criteria, the City of Spokane, Washington, was chosen. It has a population of 170,000 people and an average population density of 3360 people per square mile. Figure 1.7-1 shows a map of the City of Spokane where the stress is on the distribution of land use and of the noise sources. Further details on the city selection are covered in Appendix A.

Although Spokane, Washington, is considered "typical" of an average city in the United States, it is not typical of cities which have more severe noise problems. Thus, one should not attempt to extend the results of this study, directly, to the nation or to other cities which differ substantially from Spokane in their community noise characteristics.

1.8 SUMMARY OF NOISE COUNTERMEASURE COST-EFFECTIVENESS ANALYSIS FOR SPOKANE, WASHINGTON

The cost-effectiveness analysis is carried out on the City of Spokane, Washington, with the use of a computerized model briefly described in Appendix D. The initial analysis is conducted on a continuous segment encompassing about one-third the area of the City (Figure 1.7-1), containing the entire Central Business District (CBD) and approximately two-thirds of the daytime population, and comprising 808 noise exposure cells. This segment includes the effects of freeway traffic, railroad operations through town, commercial and military aircraft operations, as well as arterial and local road traffic. Additionally, buses in the CBD are treated as distinct noise sources.

1.8.1 Source Ranking

Applying this computer program to the one-third area of the City, it is possible to analyze the noise sources considered in this study in order of severity of noise impact for the 1973 and 1978 baseline cases (baseline means that no funds are expended on noise countermeasures). This is obtained by computing the relative contribution of each source to NII. The results are given in Table 1.8-1. As expected, surface transportation vehicles (i.e., low-speed automobiles and heavy trucks) constitute the two most significant sources for both 1973 and 1978, followed closely by aircraft noise sources.

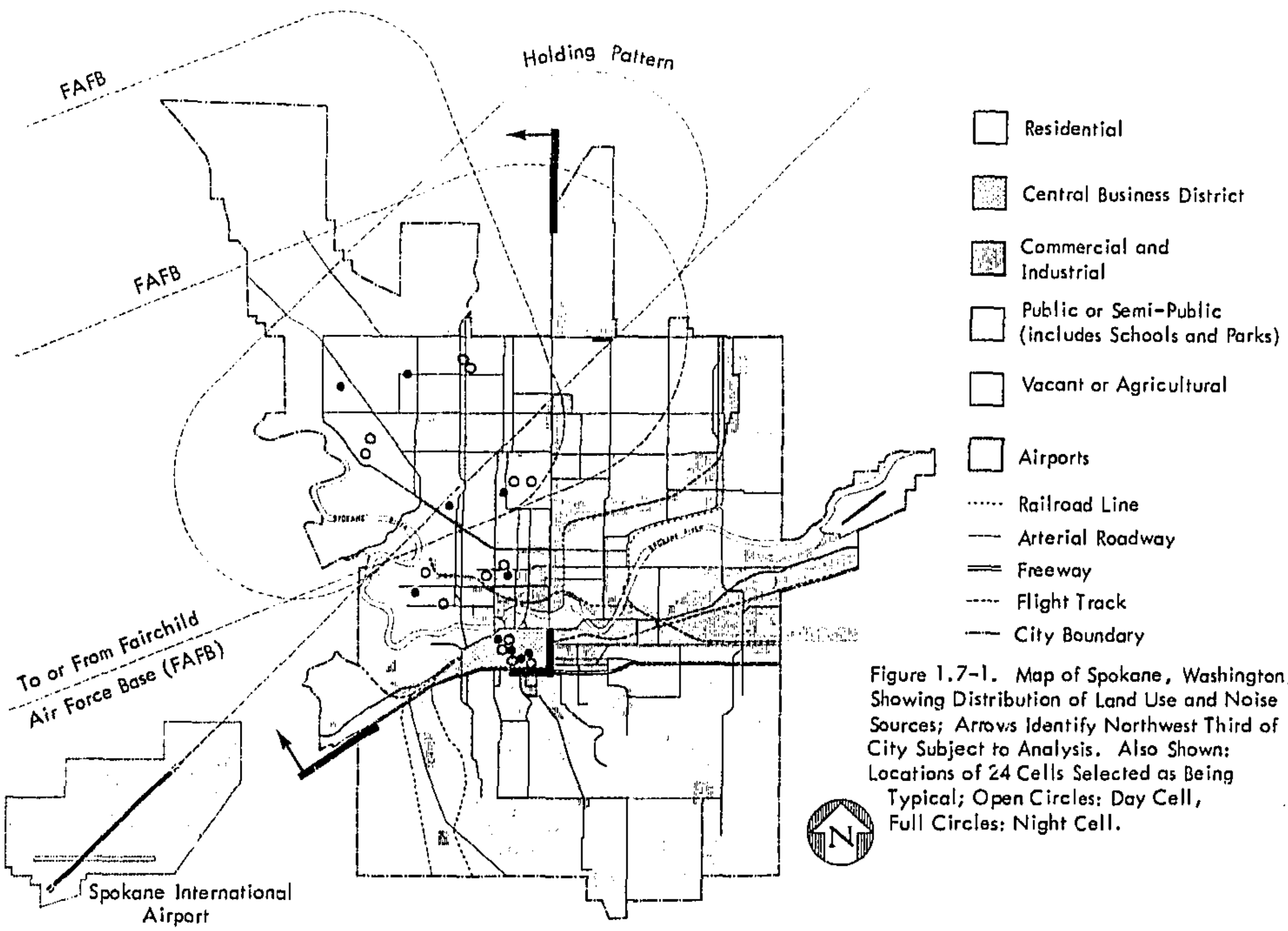

Figure 1.7-1. Map of Spokane, Washington, Showing Distribution of Land Use and Noise Sources; Arrows Identify Northwest Third of City Subject to Analysis. Also Shown: Locations of 24 Cells Selected as Being Typical; Open Circles: Day Cell, Full Circles: Night Cell.

Table 1.8-1

Relative Contribution of Dominant Community Noise Sources
To Noise Impact Index for Spokane, Washington
For the Baseline 1973 and 1978 Cases
(Based Upon Linear Noise Exposure-
Adverse Response Transfer Functions)

Environmental Noise Source Identification	Relative Contribution to NII, %	
	1973	1978
Automobiles on Arterials	23	25
Trucks on Arterials	24	21
Local Traffic	<< 1	<< 1
Military Aircraft Operations	15	15
Commercial Aircraft Operations	19	20
Automobile Tires on Freeways	4	4
Truck Tires on Freeways	4	4
Freight Trains	6	6
Passenger Trains	2	0
Buses in Central Business District	4	4
Total	100	100

1.8.2 Reduced Sample Size

In order to reduce the quantity of data that has to be processed, two variations on a 24-cell sample of the City are also evaluated in this study:

- A 24-cell model with cells selected such as to have approximately the same distribution of sources, land use and population as the one-third segment of Spokane.
- A 24-cell representation of the entire City based on adjusting the first 24-cell model to correspond approximately to the entire City.

In general, it is found that the 24-cell models of the City tend to provide results very similar to those for the large 808-cell samples at low values of cost expenditure but, without careful adjustment, tend to underrate cost-effectiveness of path and/or receiver modifications. As shown in Table 1.8-2, most of the analyses are done with the 24-cell one-third City subset using three levels of total expenditure ($5M, $10M, and $30M) along with low, medium and high estimates of the noise countermeasure cost functions.

Table 1.8-2

Cases for Which an Optimum Noise Countermeasure Expenditure Scenario Has Been Found (Linear Transfer Functions)

	$5M			$10M			$30M		
	ℓ	m	h	ℓ	m	h	ℓ	m	h
Northwest One-Third of City	x	x		x			x		x
24-Cell One-Third Subset	x	x	x	x	x	x	x	x	x
24-Cell Full City Model		x			x			x	
ℓ = low, m = medium, h = high countermeasure cost functions.									

1.8.3 Cost-Effectiveness Analysis

Scenarios of money optimally spent on the noise countermeasures discussed in Section 1.5 for three different amounts of total funds available (5, 10, and 30 million 1973 dollars) are arrived at by starting at the "baseline" case, i.e., computing the

NII for no money spent at all. Then, money is spent incrementally such as to always decrease NII in the most efficient way, i.e., spend additional funds on that countermeasure which will decrease NII the most. Because there is a limit in most countermeasures of how much noise reduction is technically feasible by the target year 1978, the amount of funds that can be expended on any one countermeasure is limited. In some cases, this limit is attained very quickly, in others, never.

It should be recognized that there may exist more than one combination of countermeasure expenditures that, for the same level of total cost, will yield a minimum Noise Impact Index. However, having gained some working experience with the computerized processing of the model, it is possible to state that the number of minima is probably small so that the "optimum scenarios" determined in this study are believed very close to the most cost-effective scenarios of countermeasures.

The most cost-effective expenditure of funds will not necessarily be on the most dominant noise sources, but rather in those areas that give the most noise reduction for the money. One must be aware of the possibility that the most pervasive source of noise may also be the most expensive to treat and that such expenditures may yield limited benefits.

1.8.4 Results – Linear Transfer Functions, Energy Equivalent Level

Table 1.8-3 shows the results of an optimum noise countermeasure expenditure scenario obtained with the 24-cell third-city subset. The same results are illustrated graphically in Figure 1.8-1. Very nearly the same trends are obtained with the other sample sets analyzed which are listed earlier in Table 1.8-2. All of these cases are tabulated in detail in Chapter 8. The following general trends may be observed.

At the lowest level of total expenditure analyzed, $5 million, ground transportation source noise reduction is most cost-effective. Aircraft noise reduction and path or receiver noise abatement treatment are not as cost-effective initially. The expenditures for noise reduction of automobiles (both low-speed and high-speed) and low-speed heavy trucks constitute the majority of effort, with the percentage

Table 1.8-3

Optimum Noise Countermeasure Expenditure Scenarios
24-Cell Representation of Northwest One-Third of Spokane, Linear Transfer Functions
Underlined Numbers: Spending Limit Reached

Level of Total Expenditure in Millions of Dollars	Counter-measure Cost Functions	Cost Allocation per Countermeasure in Millions of Dollars										Noise Impact Index
		Automobile Noise Reduction – Low and High Speed	High Speed Heavy Truck Noise – Tires	Low Speed Heavy Truck Noise Reduction	Locomotive Noise Reduction – Freight and Passenger Trains	City Bus Noise Reduction in CBD	Commerical A/C: 6/3 Approach at Spokane International	Commerical A/C: Flight Path Rerouting	Commercial A/C: Quiet Nacelle Retrofit	Commerical A/C: Night Flight Restrictions at Spokane International	Path-Receiver Treatment: Barriers – Home Insulation – Relocation	
Baseline 1978												.3440
5	Low	2.12	0	2.3	0.44	0.14	0	0	0	0	0	.2967
	Medium	3.8	0	0.97	0	0.14	0	0	0.116	0	0	.3130
	High	2.4	0	2.25	0	0.14	0	0	0.35	0	0	.3215
10	Low	4.95	0	2.3	0.44	0.25	0.367	0	1.59	0.10	0	.2670
	Medium	4.37	0	2.8	0.56	0.25	0.367	0	1.55	0.10	0	.2801
	High	4.9	0	2.8	0	0.25	0.367	0	1.58	0.10	0	.2849
30	Low	6.85	0	2.3	0.44	0.25	0.367	0.07	1.85	0.05	17.82	.2511
	Medium	6.85	0	2.8	0.56	0.25	0.367	0.04	1.85	0.05	17.21	.2642
	High	6.85	0	3.35	0.68	0.25	0.367	0.04	1.85	0.05	16.56	.2667

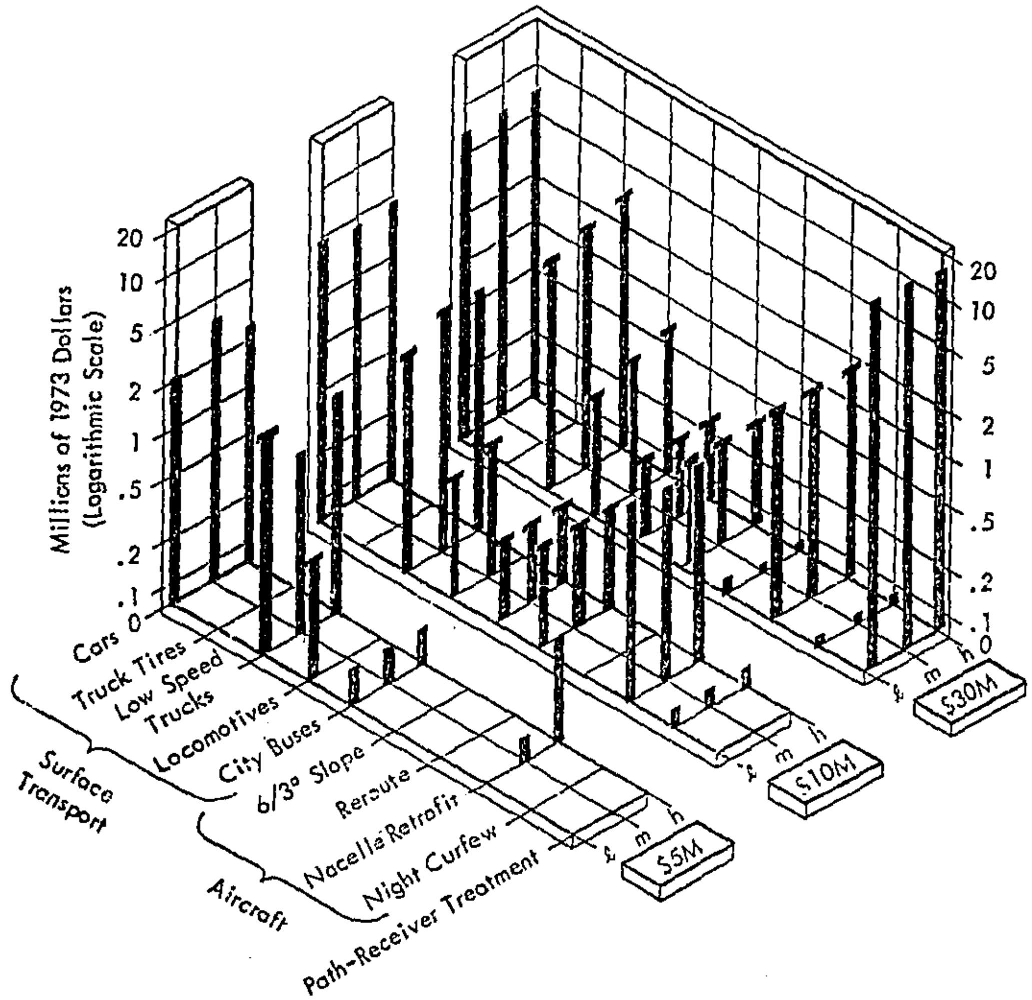

Figure 1.8-1. Optimum Noise Countermeasure Expenditure Scenarios, 24-Cell Representation of Northwest Third of Spokane, Linear Transfer Functions. ℓ, m, h Signify Low, Medium, and High Cost Ranges. Horizontal Line on Top of Bar Means Spending Limit Reached.

allocations ranging from 88 to 95 percent for the low to high-cost ranges. It is found cost-effective to treat city buses to some extent. For the low range of countermeasure costs, locomotive noise reduction is incorporated to the maximum extent; however, other items are more cost-effective in the medium and high-cost ranges. For all levels of total expenditure and all cost ranges, it never becomes cost-effective to reduce high-speed heavy truck noise (primarily the tire component) by restricting the use of cross-bar design tires on the drive axles.

At the second level of total expenditure analyzed, $10 million, one observes a broader distribution of funds, which now begin to encompass certain operational modifications for commercial aircraft. Path-receiver treatment is still not cost-effective at the $10 million level and again, as at the $5 million level, the majority of effort is directed toward automobiles, trucks, and buses, with automobiles and low-speed truck noise reductions accounting for 72 to 77 percent of the total low to high cost budgets. City buses are at their maximum possible level of treatment. A sizable amount is expended on aircraft quiet nacelle retrofit; funds are spent to the limit on implementing the two-segment approach to Spokane International Airport.

At the highest level of expenditure analyzed, $30 million, nearly all source noise reduction countermeasures are incorporated to their maximum degree except for automobile noise reduction (and high-speed truck noise as previously mentioned) which remains at approximately the same allocation as in the $10 million case. Whereas before, automobile and truck source modifications accounted for over 70 percent of the total budget, they have now dropped to 30 to 34 percent of the total. The remainder of the funds are allocated to path-receiver treatments rather than further automobile noise reduction. In fact, at this level of expenditure, these treatments account for from 59 to 55 percent of the total budget. It is interesting to note that a further analysis of which path-receiver modifications are deemed most cost-effective yields the result that dwelling sound insulation improvement in residential zones only is the single option deemed effective. Freeway or railroad barriers are not as effective for the Spokane analysis.

To summarize, the trends observed for the specific noise sources at increasing levels of expenditure are as follows:

Automobiles: Most cost-effective to treat at the low and intermediate total budgets, however, become less cost-effective at the higher levels of noise reduction attainable once the initial reduction has been obtained.

Heavy Trucks: Low-speed truck noise reduction becomes increasingly cost-effective at all levels of expenditure up to reaching the maximum technically feasible noise reduction limit (for the 1978 time period). High-speed truck noise reduction achieved through restriction of crossbar tire tread design on the drive axles never becomes cost-effective.

Freight Train Locomotives: Become increasingly cost-effective at higher levels of expenditure until the maximum limits of noise reduction are reached.

City Buses in the Central Business District: Cost-effective to silence to the maximum degree possible at the two higher levels of expenditure.

Commercial Aircraft: Implementation of a two-segment approach procedure is the most cost-effective countermeasure, followed by quiet nacelle retrofit and night flight curfew. Aircraft flight track rerouting to avoid populated areas becomes only marginally cost-effective at the highest level of expenditure.

Path-Receiver Treatments: Only become cost-effective at the highest level of expenditure once all source reduction alternatives are exhausted (except for automobiles).

1.8.5 Effects of Variation of Endpoints and Slope of Transfer Functions

To allow for uncertainty in the upper and lower limiting Criterion Levels of the exposure-response transfer functions and variation in the values of dwelling noise reduction, which were added to these indoor limits to establish the outdoor levels, it is necessary to explore the sensitivity of the results to variations in either one or both of the limiting criterion values of the transfer functions. The left-most columns of

Table 1.8-4 show what cases are considered. All of these cases, which evaluate the variations in transfer functions, utilize the 24-cell model of the one-third city segment and include all three levels of total expenditure and, in most cases, the low, medium, and high estimates of countermeasure costs.

Table 1.8-4

Cases Evaluated to Examine Sensitivity of Results to Variations in Slope, Absolute Level, and Shape of Transfer Function. Case in Heavy Box Used in Majority of Optimization Analyses (Section 1.8.3)

Difference in Level From 0% to 100% Adverse Response	Lower Limit (0% Response)	Upper Limit (100% Response)	Shape of Transfer Function		
			Linear	S-Shape	U-Shape
20 dB	50 dB*	70 dB*	x		
	40	75	x		
35	50	85	x	x	x
	60	95	x		
50	50	100	x		

*Daytime L_{eq} levels in residential areas.

In general, the cost-effective countermeasure scenarios found for all the cases analyzed in Table 1.8-4 exhibit very little difference from those using the baseline 50 to 85 dB linear transfer function used for the majority of the cases. This indicates that the way funds are distributed over the noise countermeasures is generally insensitive to the slope, absolute position or shape of the transfer function.

1.8.6 Retrofit Labor Cost Sensitivity Substudy

This substudy has been conducted in order to investigate the sensitivity of the final results to the assumption that the costs for retrofitting existing motor vehicles equal the incremental retail costs of newly manufactured motor vehicles with the same noise reducing modifications (as mentioned in Section 1.5). The procedure is to triple the retrofit costs and obtain new noise reduction versus cost functions. A revised cost-effective set of countermeasure expenditures is then obtained for the 24-cell sample of the northwest third of Spokane, using linear noise level versus adverse response transfer functions, "medium" cost functions, and a total expenditure of $10 million.

The substudy shows that expenditures on trucks are halved. The available funds are applied to commercial aircraft quiet nacelle retrofit until that noise reduction potential is exhausted. A small portion of the remaining funds is allocated to rerouting commercial aircraft, but this is not found very cost-effective. The major portion of the remaining funds is allocated to further automobile noise reduction despite the fact that this countermeasure had its retrofit costs tripled as well.

1.8.7 Study of Noise Countermeasures Based on Noise Pollution Level

The final element of this study briefly explores the potential sensitivity of the selection of cost-effective countermeasure scenarios to the underlying type of noise metric. Specifically, an analysis using the Noise Pollution Level is conducted on three individual cells chosen from the City of Spokane to represent:

1. A residential area near a major arterial and under the takeoff and approach flight paths of Spokane International Airport;
2. The Central Business District;
3. A residential area near the freeway and a railroad line.

Due to the substantial increase in data analysis required to determine the Noise Pollution Level from the summation of many sources, the analysis is limited to daytime only for these three cells. In order to explore how the picture changes when funds are expended on noise countermeasures, the following procedure is used. Using the medium cost estimating functions, the maximum allowable amounts are spent, in succession, on trucks, city transit buses, and locomotives; less than the maximum is spent on automobiles. No money is spent on airplanes and high-speed truck tire noise

Table 1.8-5

Results of Analysis Using Noise Pollution Level for the Three Cells of the City of Spokane

	ΔL_{eq} dB	ΔL_{NP} dB	Cumulative Expenditure M$
Cell 1: Residential Near Arterial and Under Flight Path			
Baseline (no money spent)	0	0	0
Spend $2.825 on Trucks	-1.5	-2.2	2.825
Spend Another $10M on Automobiles	-3.1	-3.7	12.825
Cell 2: Central Business District			
Baseline	0	0	0
Spend $0.135M on City Transit Buses	-0.7	-1.0	0.135
Spend Another $2.825M on Trucks	-1.7	-2.6	2.96
Spend Another $10M on Automobiles	-4.3	-5.7	12.96
Cell 3: Residential Area Near Freeway and Railroad			
Baseline	0	0	0
Spend $2.825M on Trucks	-0.5	-0.9	2.825
Spend Another $10M on Automobiles	-1.1	-1.1	12.825
Spend Another $0.561M on Locomotives	-1.1	-1.1	13.386

since the quieting of these sources has proven not to be cost-effective in the daytime L_{eq} analysis (see Section 8.3).

The results of this simplified analysis are summarized in Table 1.8-5. Relative reductions in both energy equivalent noise levels (ΔL_{eq}) and Noise Pollution Levels (ΔL_{NP}) are shown along with the change in total dollars spent for the succession of countermeasures applied. In a gross view of the table, it is apparent that relative changes in level, whether in terms of L_{eq} or L_{NP}, are similar for the same total dollars expended. Of course, these figures are applicable only to the particular test cell under consideration. Also, it must be remembered that no attempt is made to relate L_{NP} to human response.

The essential difference between the use of L_{eq} and L_{NP} is that any money spent on any noise countermeasure will decrease L_{eq}. This is not necessarily so with L_{NP}. Take, for example, a residential area close to an industrial complex which provides a more or less steady background noise. Lowering the latter noise may substantially increase the observed fluctuation of noise peaks (for instance from motor vehicles), which may make L_{NP} increase rather than decrease.

However, in the cases examined in Table 1.8-5, money is always spent on the most cost-effective source first. Both L_{eq} and L_{NP} decrease every time a countermeasure is applied. It would appear from this cursory look that the scenarios of the distribution of funds on noise countermeasures would not be substantially different whether the underlying noise metric is L_{eq} or L_{NP}. However, there may exist situations where an L_{NP} analysis would result in a different allocation of funds from that resulting from an L_{eq} analysis.

1.8.8 General Summary

To summarize the major results of this study on community noise countermeasures for the City of Spokane, Washington:

1. Source noise control of highway vehicles tends to be the most cost-effective community noise countermeasure for low budgets of total dollars spent.

2. Path-receiver noise countermeasures tend to become equally or more cost-effective for high budgets of total dollars spent.

3. The precise form and absolute value of human response transfer functions evaluated in this study does not appear to influence these trends substantially.

4. A new and unique systematic method has been developed for cost-effectiveness analysis of community noise countermeasures which takes into account a substantial volume of detail on spatial and temporal characteristics of noise sources and receivers. The analysis model is extensively supported by noise reduction cost data and community noise propagation concepts.

5. While the results of this study are considered representative for cities similar to Spokane, Washington, they are subject to several limitations which should be carefully considered before attempting to draw conclusions with policy implications for community noise countermeasures.

   - The results cannot be extended directly to the nation, or to other cities which differ substantially from Spokane, Washington, in their community noise characteristics.

   - Benefits of the noise reduction countermeasures evaluated are not considered in this cost-effectiveness study.

   - The overall environmental analysis considers only noise from external sources beyond those which lie within the bounds and control of residential dwellers. Noise exposure of an individual inside his own dwelling due to appliances, television or any self-generated sound or noise is not considered directly although noise exposure-human response transfer functions are modified for the time of day and general type of activity in an attempt to consider the potential influence of varying levels of self-generated noise on response to external noise sources.

- The sceanrio of countermeasures considered covers the principal ones dealing with built-in control at the source but does not consider control by field enforcement to cover such sources as faulty equipment or faulty operating procedures.
- The costs of the countermeasures considered do not include the cost of enforcement of any related regulatory action that might be required.
- The study is necessarily dated on the basis of the assumed costs and schedule for countermeasures and cannot necessarily be interpreted as representing current economic conditions.

The results of this study are based, essentially, on analytical or empirical predictions. While it would have been desirable to confirm some of the predicted noise environments, this was not possible within the scope of this study. Nevertheless, all of the environmental predictions are traceable to an experimental data base upon which they were developed.

Finally, it should be mentioned that a study like this can only be as good as the underlying noise metric. The A-weighted energy equivalent level was chosen for the greater part of the study because it has shown reasonably good correlation with human response, it is widely used for environmental studies, it is analytically simple to handle, and, at this time, a better noise metric does not exist which has comparable usage and well-documented supporting data as to its validity. However, as research advances, we may find that other metrics are superior, such as the D-weighted level, and the Noise Pollution Level. Nevertheless, until or unless quite different noise metrics are developed which might account, for example, for intrusion of outdoor noises above the ambient indoor noise in one's own home, it is not likely that the general trends developed in this study for cities like Spokane, Washington, would be substantially different with the use of only different frequency weighting (D versus A) or fluctuation weighting (NPL versus energy levels).

CHAPTER 2

QUANTIFICATION OF COMMUNITY NOISE*

2.1 INTRODUCTION

A study of the history of rating noises as to their physiological and psychological effects on individuals and groups of individuals reveals a multitude of methodologies that were developed over the years. In order to avoid further confusion, only schemes found to be most useful in recent practice will be discussed. The term "noise metric" will be used to denote a physically measurable quantity used for constructing a numeric noise rating scale. Noise metrics can conveniently be categorized into momentary, single event, single situation, and composite noise metrics. The general term "noise index" will be reserved for describing a subjective measure of noise impact based on an integrated "noise metric."

2.1.1 Momentary Noise Metrics

A momentary noise metric objectively describes the noise level experienced by a listener at a particular point in time. The physical characteristics of a noise analyzed by the human hearing mechanism are its frequency spectrum (a) and its change with time (b).

a. The ear weighs each spectral component differently. The average frequency response of a healthy human ear is well approximated by curve D in Figure 2.1-1. The hump around 4 kHz corresponds to the resonant frequency of the outer ear. Sound level meters are designed to give a noise the same frequency weighting as the human ear, i.e., they should offer a filter with a shape of curve D. Not all sound level meters offer D-weighting, but A-weighting (Figure 2.1-1, curve A) is available on all standard meters. An A-weighting filter is much easier to build but does not approximate the ear's response as well as D-weighting. Several studies have compared A- and

*All relative and absolute sound levels in dB are A-weighted levels unless otherwise specified.

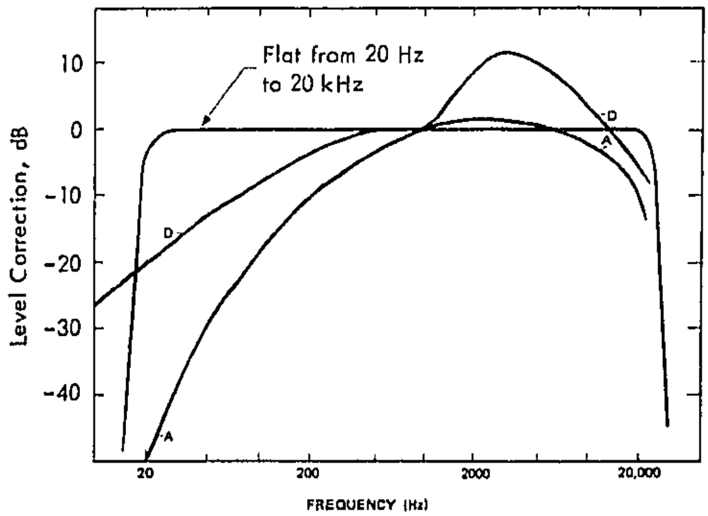

Figure 2.1-1. Frequency Weighting Curves

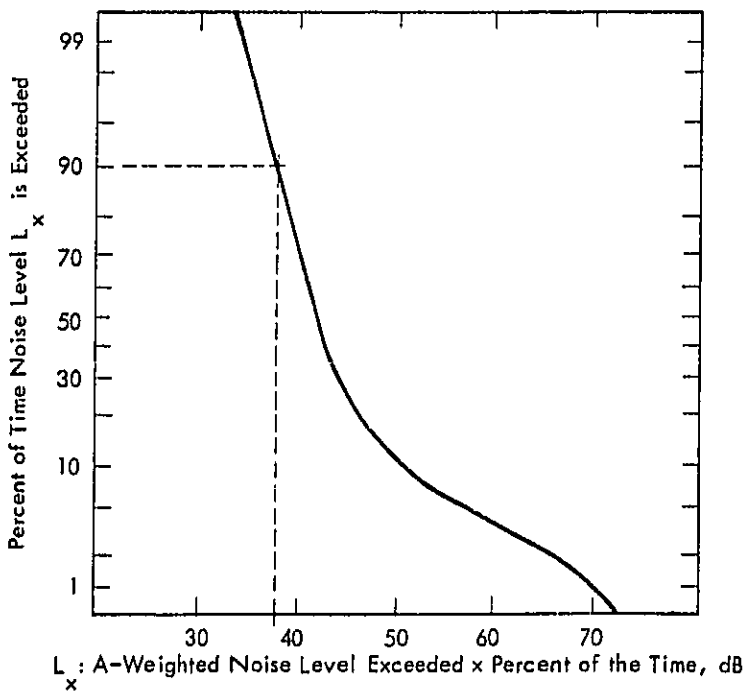

Figure 2.1-2. Cumulative Statistical Distribution Function of Noise Levels. A Straight Line Would Indicate a Normal (Gaussian) distribution.

D-weighting as to their ability to predict subjective noisiness of different sounds.[H1, P2, K1] For jet aircraft noises, the D-weighted level is the better predictor because spectra from jet aircraft contain significant acoustic energy in the vicinity of the "hump" mentioned above. However, for motor vehicle noise, most of the energy occurs at lower frequencies so that D-weighting was found to be only marginally better than A-weighting to a statistically insignificant degree. Because of its simplicity, A-weighting was, therefore, used and is assumed throughout this study unless otherwise specified.

b. As far as temporal change of a noise is concerned, the immediate psychological response (i.e., before any rational or emotional reaction) is to take a running average of the instantaneous A-weighted sound pressure P_A with a time constant T. This may be mathematically expressed by:

$$L_A(t) = 10 \log \left\{ \frac{1}{T} \int_{t-T}^{t} \left(\frac{P_A(\tau)}{P_{ref}} \right)^2 d\tau \right\} \qquad (2\text{-}1)$$

T is of the order of 0.1 to 0.5 seconds. L_A is the "momentary" noise level. t is the real time, τ a dummy integration variable. P_{ref} is the reference pressure of 20 μPascals.*

Most sound level meters offer "fast" and "slow" response for the measurement of the momentary level. The respective integration times T are approximately 0.2 and 0.5 seconds.

An exception must be made for loud impulsive noises such as gunshots, helicopter blade slap, sonic booms, and occasional bangs from construction sites. Then Eq. (2-1) does not describe the human response. The suddenness of the onset of a high sound level often results in a startle reaction. Ordinary

*1 Pascal = 1 Newton per square meter.

sound level meters with "fast" or "slow" response only do not respond to impulses in a way comparable to humans. One way to account for this is to introduce an "impulse correction" by analogy to tone and duration correction. However, such noises are generally rare in the community environment. They are not given further consideration here.

Another commonly used noise assessment method uses the Perceived Noise Level (PNL) with PNdB as unit.[K2] It was developed mainly for the purpose of rating aircraft noise. To use PNL as a momentary noise metric requires very elaborate instrumentation which is generally employed only for aircraft noise certification tests. As far as motor vehicle noise is concerned, PNL has not shown a statistically significantly better correlation with annoyance scores than the simple A-level.[H1, P2, G1]

In summary, the present study uses as the momentary noise metric the A-weighted level at "fast" response.

2.1.2 Single Event Noise Metrics

A single event noise metric objectively describes the noise of a single transient event with a well-defined beginning and ending. Examples are the peak A-level, the peak PNL, the tone and duration corrected PNL, and the energy-mean level for the event. A single event can also be described by its statistical cumulative distribution function of noise levels.

In motor vehicle noise testing, the drive-by test uses the peak A-weighted level as the single event noise metric. Another reasonable choice would be the equivalent (i.e., energy mean) A-weighted level. PNL is discarded for reasons discussed in the previous section. The cumulative distribution function is of practical use in a limited number of cases, particularly in mathematical models, when it is possible to approximate the temporal variation of the noise event in dB by a small number of straight line segments. Then it is easy to compute the distribution function.

2.1.3 Single Situation Noise Metrics

A single situation noise metric objectively describes the noise heard by an observer in one particular situation where the noise is generated by an ongoing source or a continuous stream of single events. Examples are: a person sleeping in a house adjacent to a freeway, riding as a passenger in an airplane, and working for 8 hours at a construction site. The following discusses the single situation metrics which have been used in recent common practice:

A cumulative statistical distribution function of noise levels is shown in Figure 2.1-2. L_x is the noise level that is exceeded x percent of the time. The example in the figure shows that a level of 37 dB is exceeded 90 percent of the time; therefore: L_{90} = 37 dB (the level corresponding to the 90th percentile). The periods over which statistical distributions are obtained range typically from 1 hour to 1 day. The whole distribution can be regarded as a noise metric. Most of the time, however, a single number describing a single situation is preferred. Thus, different percentile levels are chosen for different purposes. For example, the Federal Highway Administration uses L_{10} as a measure of environmental quality adjacent to highways. The disadvantage of using a single percentile level is that nothing is said about the shape of the distribution function, i.e., there is no information on how much the percentile level is exceeded or what the background noise is.

The energy equivalent level L_{eq} is the level that would result in the same acoustic energy emission, if applied continuously, as the actual fluctuating level. The mathematical handling of L_{eq} is convenient, L_{eq} can easily be measured in the field, and human response correlates reasonably well with L_{eq} although not in the best manner known to date. L_{eq} was chosen as one of the metrics underlying the countermeasure effectiveness analysis in this report. More detailed discussion follows in Section 2.2.

Another advantage of L_{eq} is that noises from any source can be compared on the same scale. However, noises with large level fluctuations are potentially more annoying than indicated by the equivalent level. In an attempt to account for this variability, the Traffic Noise Index (TNI) was defined:[G7]

$$TNI = 4(L_{10} - L_{90}) + L_{90} - 30 \qquad (2-2)$$

where the first term on the right hand side heavily weighs the amount of noise level fluctuations. TNI does not correlate with human response nearly as well as the Noise Pollution Level (L_{NP}) defined by Robinson.[R3] He extended the ideas incorporated in TNI and developed the following expression based on statistical theory assuming a normal noise level distribution:

$$L_{NP} = L_{eq} + 2.56\sigma \qquad (2-3)$$

where σ is the standard deviation of the distribution function. L_{NP} is adopted as one of the single situation noise metrics in this report for the purposes of the community noise countermeasures effectiveness analysis. Further discussion follows in Section 2.3.

Another single situation metric results from using the preferred noise criterion curves (PNC).[B3] While this system adequately rates steady background noises, it is not well suited to fluctuating noises. Also, an octave band analysis is required which is too tedious for the purposes of the countermeasure analysis later in this report.

2.1.4 Composite Noise Metrics

Composite noise metrics objectively describe the time integrated value of noise exposure over a 24-hour day. We need to discuss here only those metrics derived from quantities we have accepted earlier in this chapter. This automatically excludes metrics defined specifically for estimating aircraft noise exposure (NEF, NNI, CNR, WECPNL) since they are based on PNL which we have rejected in favor of the A-weighted level.

Single situation metrics can be extended and modified to become composite metrics. For instance, L_{eq} can be obtained for a whole day. The day-night equivalent level L_{dn} is derived from L_{eq} by applying a 10 dB penalty to nighttime noises.[U6] The Community Noise Equivalent Level (CNEL) is defined similarly with an additional "evening" period with a 5 dB penalty.[C1] The Noise Pollution Level L_{NP} could also be computed over a whole day and used as a composite noise metric.

For the purposes of the noise countermeasure analysis of this report, it was found most useful not to employ composite noise metrics directly, but to use single situation metrics, relate them to human response, impose weighting by population density and arrive at a Noise Impact Index estimating the severity of noise exposure. Details will be found in Section 2.4.

2.2 THE ENERGY EQUIVALENT NOISE LEVEL

The Energy Equivalent Noise Level L_{eq} is defined as the constant level that, if applied continuously over the time period contemplated, would result in the same acoustic energy emission as the actual fluctuating level L(t). L(t) is a momentary noise metric (see Section 2.1.1), L_{eq} is either a single event or single situation noise metric (see Sections 2.1.2 and 2.1.3). We can write:

$$L_{eq} = 10 \log \left\{ \frac{1}{T} \int_0^T 10^{L(t)/10} dt \right\} \qquad (2\text{-}4)$$

where t is the real time, L(t) the varying noise level in dB, T the integration time (typically in the range from 1 hour to 1 day for single situation metrics, the duration of the noise event for single event metrics). The relative simplicity of Eq. (2-4) makes L_{eq} easy to handle in theoretical investigations and on the computer. L_{eq} from several sources is easily obtained by replacing the integrand in Eq. (2-4) by a sum of similar exponentials, one for each source.

Here are some properties of L_{eq} which follow from Eq. (2-4):

- Other things held constant, a doubling of T increases L_{eq} by 3 dB, a halving of T reduces L_{eq} by 3 dB.
- Other things held constant, L_{eq} is proportional to L; i.e., a 10 db increase of L also increases L_{eq} by 10 dB.

- Addition of component L_{eq}'s to form an overall L_{eq} is performed using a very similar formula:

$$L_{eq} = 10 \log \left\{ \sum_{s=1}^{N} 10^{L_{eq,\,s}/10} \right\} \qquad (2\text{-}5)$$

(N = number of components.) Example: combination of traffic noise, aircraft noise, and the noise from the dog next door.

- Due to the logarithmic nature of level addition (Eq. (2-5)), the higher levels dominate L_{eq}. For example, if L_1 is 10 dB below L_2, then $L_1 + L_2 \simeq L_2$ with a negligible error.

Although the measurement of L_{eq} of a fluctuating level is not a trivial process, instrumentation for direct measurement of L_{eq} is readily available. Specifications for one such system can be found in Reference C1.

An in-depth discussion of L_{eq} can be found in Appendix A of Reference U6. The following summarizes important points of that appendix. The concept of the equivalent sound level has been accepted in many countries as the standard method of rating noises. L_{eq} correlates well with other noise metrics as far as subjective response is concerned. There is evidence that L_{eq} accurately describes the onset and progress of noise-induced hearing loss, and substantial evidence to show that it applies to annoyance in various circumstances (actual numerical transfer functions between noise level and annoyance response are presented in Chapter 3).

L_{eq} can also be obtained from a statistical distribution function. If p is the fraction of time (or the probability) that the noise level was between L and L + dL, then:

$$L_{eq} = 10 \log \left\{ \int_{-\infty}^{\infty} p \; 10^{L/10} \, dL \right\} \qquad (2\text{-}6)$$

If L always was above L_1 and below L_2, then the limits $-\infty$ and ∞ are replaced by L_1 and L_2, respectively. Equation (2-6) is applied in the formulation of L_{NP} (see Section 2.3). The method of predicting L_{eq} of specific sources is described in Chapter 4.

2.3 THE NOISE POLLUTION LEVEL

The development of the Noise Pollution Level L_{NP} is due to D.W. Robinson. A summary of his landmark paper, published in 1971, is given in the following paragraphs.[R4]

The use of the energy-mean equivalent level was a significant step toward reconciling the differences between noise rating scales and human response data from social surveys. However, the accord could not and today still cannot be considered sufficient with a reasonable statistical confidence. The reason for this is that the variability of the noise level is an important factor influencing the amount of adverse reaction to a noisy environment. The simplest way that both the total amount of sound and the level fluctuation can be combined into one number is by the equation:

$$L_{NP} = L_{eq} + K\sigma \qquad (2\text{-}7)$$

where L_{eq} comes from Eq. (2-4), K is a constant which remains to be determined, and σ is some measure of noise level dispersion.

Any momentary noise metric (see Section 2.1.1) can be used in Eq. (2-7) to arrive at L_{eq} and σ. In this report, the A-weighted level is implied. Because the standard deviation is an efficient statistic for estimating variance for many typically occurring distributions, it is used as the measure of dispersion σ.

The value for K is arrived at by fitting Eq. (2-7) to psychological response data. To date, a value of K = 2.56 seems to be the best choice (it is used in this report) although future research may show a need for adjustment of this constant.

Robinson shows that L_{NP} fits very well sociological data related to road traffic noise as well as to aircraft noise. The need for different indices for different situations thereby evaporates. Several other workers have found that L_{NP} is one of the better noise indices among those which can be computed with reasonable ease:

- Anderson 1971:[A1] L_{NP} predicts psychological response better than L_{eq} when intermittent noises are presented at varying repetition rates. The author thinks that K = 2.56 is an underestimate. K = 4 would fit his data better.
- Waller 1971:[W2] All psychophysical effects are noted by humans with respect to a mean level and deviations therefrom, i.e., not just noise, but also for instance, the thermal environment and air quality. L_{NP} is much preferred over L_{10} or TNI.
- Fuller and Robinson 1973:[F5] When noise peaks are superimposed on a steady noise, L_{NP} predicts adverse reactions better than L_{eq}.
- Cannelli and Santoboni 1974:[C4] A new metric L_{DI} is proposed similar in principal structure to L_{NP}, but peak noise levels are introduced in the term accounting for variability. The authors admit that L_{NP} is the metric with better correlation to human response but assert that L_{DI} is easier to measure.
- Jenkins 1974:[J1] The noise climate around residences near Los Angeles freeways was recorded and then analyzed in terms of L_{10}, L_{50}, L_{90}, TNI, and L_{NP}. A sociological survey was also conducted which differentiated between spontaneous and elicited response. TNI fared worst. L_{NP} did best on spontaneous responses, L_{50} on elicited responses, with L_{NP} trailing closely. This study did not consider L_{eq} by itself.

It appears, therefore, that L_{NP} is a good choice as a single situation metric for the prediction of community response to noise. A word of caution, however:

although L_{NP} seems well supported for analysis of individual sources (noise from road traffic, aircraft), it has not been demonstrated that it works as well when the total noise environment is considered. Nevertheless, a study considering this total noise environment has been conducted and is described in Chapter 8. The method of predicting L_{NP} resulting from the combination of many sources is described in Chapter 5. There, it is seen that L_{NP} prediction is a much more complicated process than L_{eq} prediction. This is one of the reasons why L_{eq} is used in the greater portion of the noise countermeasure effectiveness analysis of Chapter 8.

2.4 NOISE IMPACT INDEX

The Noise Impact Index (NII) is defined for the purpose of creating a tool with which to rate numerically the desirability or undesirability of a given noise environment. In its most general form, NII is defined by:

$$NII = \int_T \int_A \Phi(x, y, t, L)\, P(x, y, t)\, dx\, dy\, dt \Big/ \int_T \int_A P(x, y, t)\, dx\, dy\, dt \qquad (2\text{-}8)$$

A is the surface area under consideration (a city block, a segment of the city, the whole community), dx dy is a surface element pointing to a specific location. T is the integration time (usually 24 hours). P is the number of people in dx dy at time t. Φ is called the "transfer function." It relates to a given noise level L the fraction of people responding adversely to that level (Figure 2.4-1). Φ is assumed to depend only on the noise level L at dx dy and t, the land use at dx dy (independent of t), and the time of day at t. Expressing Eq. (2-8) in words: NII gives the proportion of adversely responding people over a certain area and over one day; NII is obtained by computing the people-weighted annoyance transfer function. This NII is used to rate the effectiveness of noise countermeasures (see Chapter 8). Appendix D describes the computer program which evaluates Eq. (2-8). Transfer functions for particular applications are discussed in Chapter 3.

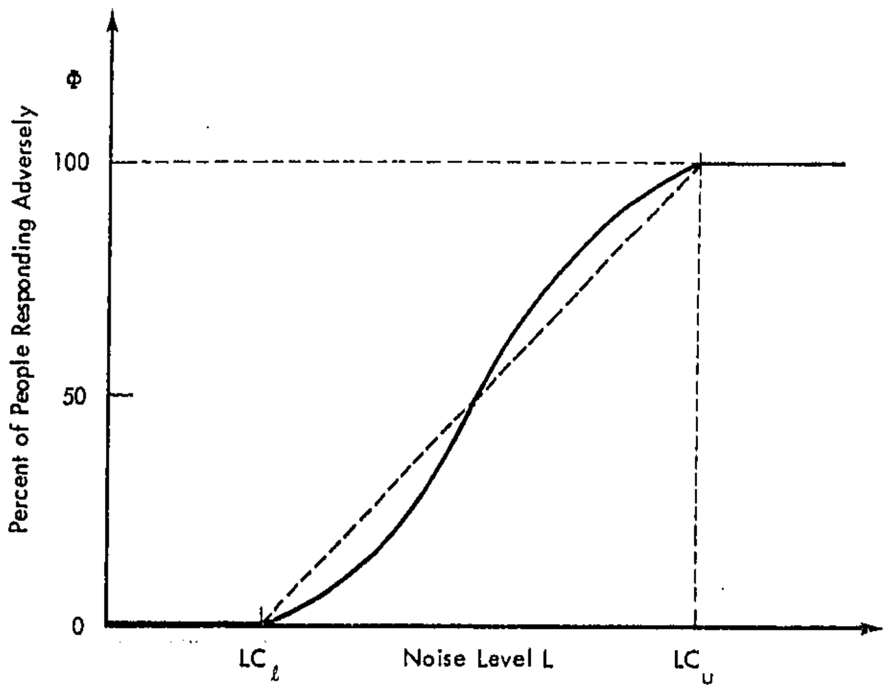

Figure 2.4-1. Transfer Function $\Phi(L)$ Relating Human Response to Noise Level. No Adverse Response Below Lower Criterion Level LC_ℓ, 100 Percent Adverse Response at and Above Upper Criterion Level LC_u. LC_ℓ, LC_u and Function Shape Vary with Land Use and Time of Day.

CHAPTER 3

HUMAN RESPONSE TO COMMUNITY NOISE*

3.1 INTRODUCTION

No creature can close its ears like it can close its eyes. The ears keep a constant watch for us, whether we are awake or asleep. The ear and its associated processing area in the brain, therefore, never rest completely. It is up to us to offer them periods of minimum activity, i.e., quiet, if we wish to retain our full hearing faculties for as long as we live. It is also up to us to ensure the enjoyment of our world by reducing or eliminating noises which mask or interfere with sounds we wish to hear. Fortunately, humans possess a built-in protective reaction against noise: We feel an adverse response when we are exposed to unwanted sounds. Such an immediate protective reaction does not exist against many other environmentally deteriorating factors. However, very often we are unable to start an action against a noise. You can ask your son to stop pounding on the empty tin can, but what fast action can you pursue against the thousands of cars and trucks roaring by your house? The protective reaction may then be suppressed, the noise receiver may give up, get used to the noise, and live with it. But there is evidence that parts of the human body never get used to noise, never adapt to it, although the conscious mind has "shut the noise out."

Government bodies with regulatory power can help. However, regulations should be based on solid scientific facts about the effects of noise on people, in particular about long term health effects. Unfortunately, little is known on the subject, certainly not sufficient detail for a comprehensive analysis of possible regulations. Only the situations which may lead to permanent hearing damage are reasonably well documented. There exists also a small amount of usable information on the disturbance of sleep by noise.

*All relative and absolute sound levels in dB are A-weighted levels unless otherwise specified.

But the purpose of the work described in this report is precisely such an analysis of regulations; we wish to explore the effects of motor vehicle noise countermeasures. Considering the effects of noise on people, we must therefore include besides effects on health some other measure of adverse effects of noise. The only other one which has been documented quite well and is amenable to numerical analysis is the number of people out of a population exposed to the same noise level who register noise as an adverse factor in their living environment.

Many sociological surveys have been conducted with the goal of relating a measurable noise metric to adverse human response. One general statement that may be made is that the average community response correlates quite well with that metric if the latter is chosen wisely, but that the response of individuals correlates badly with that same metric.

An adverse response to noise will occur when an activity is being interfered with by the noise. The term "activity" must be interpreted broadly, i.e., also including apparently inactive periods like sleeping. Since individuals are occupied with a wide variety of activities, we can expect that their responses to noise will diverge. In addition, an individual's response depends strongly on his attitude toward the source of the noise and its operator. It is therefore only possible to treat the community responding to noise as one entity realizing that individual responses will stray far from the community average.

The term "annoyance" tends to be used to describe adverse response to noise. Different sociological surveys probe for different degrees of annoyance, and also for different kinds of annoyance (i.e., annoyance with one noise event, or general dissatisfaction with the area due to noise) by employing different ways of approaching and questioning people. Although the correlation of sociological response data with noise level may be high for each survey, quite a difference may be found in the actual functional relationship between the percentage of people annoyed and the noise level. Also, social surveys are often difficult to compare with each other because they choose different metrics as the measure of the noise level. In this report, the term annoyance means the long term integrated adverse response, where "long term" is anywhere from several weeks to several years. As set out in Chapter 2, the basic noise metric for this report is the energy-mean A-weighted noise level.

3.2 DEVELOPMENT OF TRANSFER FUNCTIONS

One of the elements in the logical chain leading from the description of the noise environment (i.e., the quantification of the noise exposure) to the Noise Impact Index is the relationship between noise level and the percentage of people responding adversely to that level. This relationship is called the transfer function. An example was shown in Figure 2.4-1. It is assumed that nobody responds adversely below a noise level of LC_ℓ, the lower Criterion Level, and that everybody responds above a noise level of LC_u, the upper Criterion Level. The task is now to define LC_ℓ, LC_u, and the shape of the transfer function in between.

For each land use category, a separate transfer function is defined since peoples' sensitivity to noise is different in residential areas from that in commercial and industrial areas. Also, different transfer functions apply for different times of day: peoples' activities during the day are mostly work, often with the requirement of speech communication, while during the night, it is mostly sleep.

The procedure for obtaining the Criterion Levels for one land use and one time of day generally consists of four steps:

1. Define the activities pursued.
2. Define the upper and lower Criterion Levels associated with each activity (LC_i).
3. Analyze the percentage of time spent in each activity (t_i).
4. Sum the LC_i's in analogy and in accord with the definition of L_{eq} [see Eq. (2-4)] to obtain the overall LC:

$$LC = 10 \log \sum_i t_i * 10^{LC_i/10} \qquad (3\text{-}1)$$

Not all LC's are arrived at by the above procedure. The detailed discussion below will spell out all deviations and assumptions made. In particular, the upper Criterion Levels are often chosen according to health criteria rather than annoyance criteria. This then implies that the ordinate scale in Figure 2.4-1 does not always indicate the percentage of people annoyed, but, to some extent, incorporates the percent of people risking a loss of hearing ability, even though they may not be annoyed by high noise levels. This is why the term "responding adversely" is used rather than "annoyed."

3.2.1 Analysis of Time Spent in Activities

Based on data in References S13, L2, S6, and L1, an extensive analysis of activities was performed. The details are not reported here. The results, which are applicable to the County of Spokane only (see Appendix A), are given in Tables 3.2-1 and 3.2-2. Activities are grouped into nine categories (eight for "at home") for which distinctively different Criterion Levels are expected. Daytime is counted from 7:00 a.m. to 10:00 p.m., nighttime from 10:00 p.m. to 7:00 a.m. This defines the t_i's in Eq. (3-1).

3.2.2 Definition of Criterion Levels

Table 3.2-3 shows acceptable A-weighted noise levels for many activities as obtained from six different references. These are used in the composition of the lower Criterion Levels LC_ℓ. Strictly speaking, activities should be divided into indoor and outdoor activities, the time spent in each should be determined, and thereafter Eq. (3-1) could be used. However, the percentage of time spent outdoors including pedestrian activity turns out to be very small so that its contribution is neglected. The procedure then is to define LC's for indoors only in each land use category. They are translated into outdoor LC's by adding the amount of building noise reduction

Table 3.2-1

Percent of Time Spent in Nine Activity Categories for Full 24 Hour Period *

	Day	Night	24 Hours
TV Viewing	6.76	5.36	6.24
Leisure (Conversation)	13.68	6.68	11.05
Leisure (Concentration)	7.76	3.47	6.15
Home and Family (Conversation)	6.52	0.66	4.32
Home and Family (Higher Background Noise Level Allowed)	17.01	1.72	11.28
Traveling	7.19	1.55	5.08
Working	25.20	2.87	16.83
Eating	8.53	1.12	5.75
Sleeping	7.35	76.58	33.31
Total	100.00	100.00	100.00

Table 3.2-2

Time Spent in Eight Activity Categories for the Time Spent at Home *

	Day		Night		Total	
	Hours	%	Hours	%	Hours	%
TV Viewing	1.0	11.8	0.5	6.0	1.5	8.9
Leisure (Conversation)	1.3	15.3	0.4	4.8	1.7	10.1
Leisure (Concentration)	1.1	12.9	0.2	2.4	1.3	7.7
Home and Family (Conversation)	0.8	9.4	0.1	1.2	0.9	5.4
Home and Family (Higher Background Noise Level Allowed)	2.2	25.9	0.1	1.2	2.3	13.7
Working	0.1	1.2	0	0	0.1	.6
Eating	0.9	10.6	0.1	1.2	1.0	6.0
Sleeping	1.1	12.9	6.9	83.0	8.0	47.6
Total	8.5	100.0	8.3	100.0	16.8	100.0

*Based on national data adjusted to conditions in County of Spokane.

Table 3.2-3

Acceptable A-Weighted Noise Levels for Various Activities
(Values in Parentheses Adapted from Similar Activities)

	Reference R2	Reference S3	Reference B2	Reference D5	Reference R2	Reference B8
Private Office	38-42	38-42	38-47	30-38	46	
Semi-Private Office	42-47	42-52	42-52	38-42		35
Typing Pool	47-52	47-56	47-56	52-66		45-55
Drafting Area	47-52	(47-56)	47-56	47-52		
Library	38-42		38-47	38-42		
Lobbies	47-52		47-56			
Restaurants	42-47	42-52	42-52	42-56	50	35-45
Markets	(42-47)	(42-52)	42-52		54	
Department Stores	(42-47)	42-52	42-52		54	35
Household Duties		47-56	(52-61)			
Sleep	30-38	34-42	34-47	34-42	34-42	
Speech	(38-42)		(38-47)			
TV Viewing	38-42		38-47			
Relaxing Outdoors	(38-42)		(38-47)			
Hospitals and Hotels	30-38	34-42	34-47	34-42	38-42	
Churches	(34-38)	34-42	42	34-42	38	
Outdoor Recreation		42-56	42-52	56	46	
Schools (Inside)	38-42		38-47	34	38	
Industry	52-61	52-71	56-66			

typical for each land use category. After the following two subsections, Table 3.2-5 can be found listing all relevant indoor Criterion Levels.

3.2.2.1 Residential Areas

The eight activity categories of Table 3.2-2 are further classified into three groups with distinctively different noise susceptibilities:

Group 1: Sleeping, working, leisure with concentration required. These activities are the ones most highly disturbed by noise.

Group 2: TV viewing, leisure with conversation required, home and family with conversation required, and eating. These activities are not as easily disturbed by noise as those in Group 1.

Group 3: Home and family with higher background noise level allowed. These activities produce noise themselves.

For Group 1, the lower criterion limit, LC_ℓ, is selected from the lower range of published levels (Table 3.2-3) as 30 dB for an acceptable sleeping environment. For Group 2, LC_ℓ, of 35 dB is established to provide an environment compatible with relaxed conversation. The LC_ℓ for Group 3 is fixed 10 dB higher at 45 dB to include consideration of some self-generated noise exposure.

The upper criterion limit for Group 1, LC_u, is selected as 60 dB, being 30 dB above the LC_ℓ and being high enough to awaken from sleep or to typically cause a shift in sleep level (see Reference K2, page 518). For Groups 2 and 3, LC_u is determined by speech interference and hearing damage criteria. A level of 75 dB is chosen: this level requires a "very loud" voice for adequate speech communication over a distance of 6 feet (Reference K2, page 92). 75 dB is also the level that, if not exceeded, should protect almost the entire population from incurring more than a 5 dB noise-induced permanent threshold shift in hearing acuity, if exposed 8 hours a day over 40 years (Reference U6, Figure 3).

A summary of the above data is given in Table 3.2-4, also displaying the overall Criterion Levels for day and night which are obtained via Eq. (3-1). For multi-unit dwellings, the LC_u is chosen 5 dB higher under the assumption that the majority of persons will accept higher levels than those in single-family dwellings. LC_ℓ remains the same.

Table 3.2-4

Indoor Lower and Upper Criterion Levels for Residential Areas, Single-Family Dwellings

	LC_ℓ, dB	LC_u, dB
Group 1	30	60
Group 2	35	75
Group 3	45	75
Overall Residential Daytime	40	74
Overall Residential Nighttime	32	67

Especially noise-sensitive locations are associated with Criterion Levels of their own. For hospitals and nursing homes, it is assumed that the principal activity at night is sleeping. Therefore, the LC's of Group 1 apply (LC_ℓ = 30 dB, LC_u = 60 dB). During the day, it is assumed that half the occupants are asleep while the other half is engaged in activities of Group 2. LC_ℓ is calculated according to Eq. (3-1) resulting in 33 dB. If Eq. (3-1) were applied to LC_u, it would come out to 72 dB. However, occupants of hospitals and nursing homes are expected to have a lower tolerance for noise so that the LC_u for daytime is set to 63 dB, 30 dB above LC_ℓ.

Schools are assumed to operate during the daytime only. LC_ℓ is chosen as 38 dB, based on the criterion of acceptable speech communication over normal distances in a classroom. A level of 66 dB is about the upper limit of adequate communication without undue vocal effort over a distance of about 6 feet (Reference K2, page 92).

3.2.2.2 Non-Residential Areas

For offices and businesses in commercially zoned areas, the same speech communication criteria as for schools are assumed to apply; therefore: LC_ℓ = 38 dB, LC_u = 66 dB. However, they apply to both day and nighttime.

Industrial activities are split into light and heavy industry. Recommendations as to acceptable noise levels vary widely. For light industry, the lowest level in Table 3.2-3 is selected for LC_ℓ: 52 dB. For heavy industry, 66 dB is chosen exercising some subjective judgment. For LC_u hearing damage criteria apply which dictate 75 dB (see previous section for Groups 2 and 3). 75 dB may seem like a very low Criterion Level in the light of the level standardized by the Occupational Safety and Health Administration (90 dB for 8 hours). The latter level is considered "economically reasonable" at this time. Efforts are under way to lower OSHA's hearing damage Criterion Level. In this report, the true human response to noise is sought without concessions to economic reasonableness.

Hotels and motels are considered noise-sensitive locations in nonresidential areas. The daytime Criterion Levels are assumed to be the same as for single-family dwellings (LC_ℓ = 40 dB, LC_u = 74 dB). Nighttime activity is assumed to be sleep, but 5 dB are added to the sleep Criterion Levels (see nighttime hospitals and nursing homes) to account for the transient nature of the occupants: LC_ℓ = 35 dB, LC_u = 65 dB.

The following Table 3.2-5 displays the selected Criterion Levels for all land use categories.

Table 3.2-5

Indoor Criterion Levels

Land Use or Building Use	Lower Criterion Level, dB		Upper Criterion Level, dB	
	Day	Night	Day	Night
Residential, Single-Family Dwellings	40	32	74	67
Residential, Multiunit Dwellings	40	32	79	72
Hospitals and Nursing Homes	33	30	63	60
Schools	38	-	66	-
Commercial Areas: Offices, Businesses	38	38	66	66
Hotels and Motels	40	35	74	65

3.2.2.3 Outdoor Criterion Levels

It is convenient to work only with outdoor noise levels because they are more easily predicted than indoor levels. The noise reduction of buildings is added to the indoor Criterion Levels to arrive at the outdoor levels. Section 6.7 discusses the noise reduction capability of various categories of buildings. There, Table 6.7-1 can be found giving values of noise reduction in terms of A-weighted dB. Because buildings, even within one category, still show a great deal of variance, only a range of noise reduction values can be given which leaves considerable freedom for selecting a noise reduction. The following additional conditions may therefore be imposed:

- For computational convenience and to better be able to follow trends in the noise countermeasure analysis described in Chapter 8, a constant difference between LC_u and LC_ℓ is maintained for each pair of values (35 dB).
- An upper practical outdoor limit for LC_u is taken as 90 dB. This allows industrial activity to be lumped with commercial activity.

Table 3.2-6 shows the selected outdoor Criterion Levels.

Table 3.2-6

Outdoor Criterion Levels

Land Use	LC_ℓ, dB		LC_u, dB	
	Day	Night	Day	Night
Residential, Single-Family Dwellings	50	42	85	77
Residential, Multiunit Dwellings	55	42	90	77
Commercial and Industrial	55	55	90	90
Schools	50	-	85	-
Hotels and Motels	55	50	90	85
Hospitals and Nursing Homes	53	50	88	85

3.2.3 Shape of Transfer Function

Looking again at Figure 2.4-1, we have so far defined LC_ℓ and LC_u of the transfer function. The shape in between remains to be discussed.

Figure 3.2-1 shows the percent of people listing an adverse response versus the day-night equivalent sound level (see Section 2.1.4 for L_{dn}). It appears from the

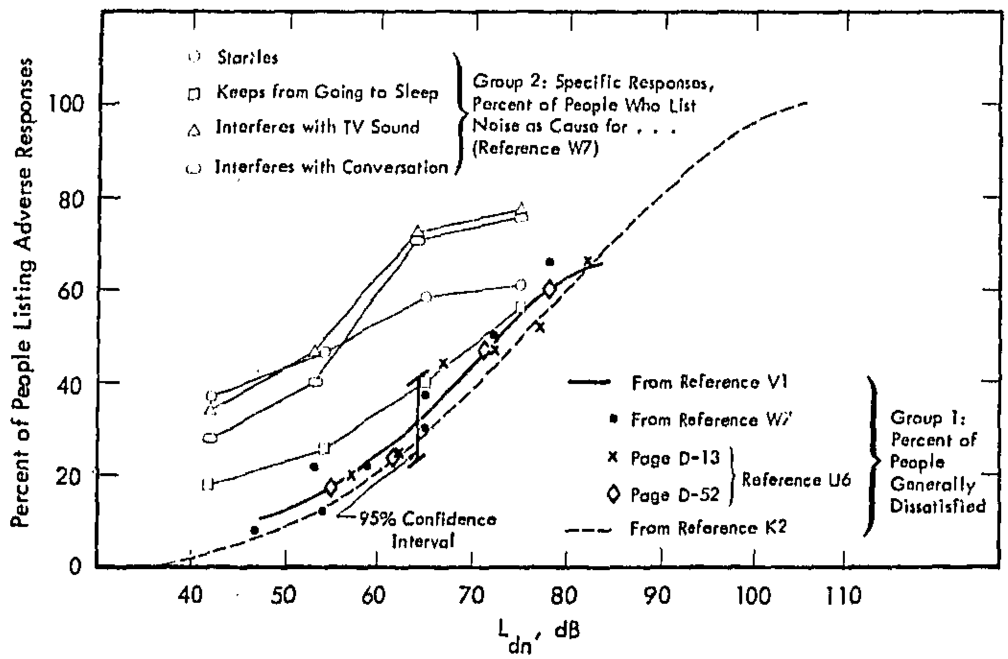

Figure 3.2-1. Percent of People Listing Adverse Responses, Versus Day-Night Equivalent Sound Level (See Section 2.1.4 for L_{dn}).

spread and uncertainties in the data of Group 1 in Figure 3.2-1 that a straight line approximation for the transfer function shape is very reasonable. Because of its computational simplicity, the linear relationship is incorporated in the greater portion of the final analysis (Chapter 8). However, the data from both Groups 1 and 2 suggest that a slightly nonlinear S-shaped transfer function is a better approximation. Ollerhead also presents substantial evidence that human response to noise exposure transfer functions are rather more S-shaped than anything else.[O1] In Chapter 8, the use of different nonlinear mathematical representations of the S-function is further explored in connection with the optimized expenditure of funds on community noise countermeasures.

CHAPTER 4

QUANTIFICATION OF TRANSPORTATION NOISE USING L_{eq}*

The outdoor noise environment in a community is generally dominated by transportation noise. For the specific purposes of the noise countermeasure effectiveness analysis of this report, the following noise sources are considered: automobiles and trucks (each at low and high speeds), city buses, railroads and aircraft. Transportation sources not considered include metropolitan rapid transit lines and motorcycles, although the latter may often be of particular annoyance on a local street. However, this problem is more one of enforcement of state muffling regulations and local noise ordinances than one which can be subjected to the present economic analysis. Also, the number of motorcycles is small so that it is assumed that their contribution to the total noise energy is negligible.

The noise exposure levels from transportation sources are computed by a series of computer programs. Their mathematical models are based on data collected over the years. The modeling accuracy is well within the statistical variability of the underlying data.

4.1 MOTOR VEHICLES

4.1.1 Automobiles and Trucks

For this program, automobile and truck noise is considered as two separate sources: (1) engine/exhaust noise, and (2) tire noise. For vehicles without any noise reduction treatment, the combined output of these two sources is determined using the Wyle highway noise simulation program. This computes the energy sum of noise from all individual vehicles traveling on any single highway.[P5] Noise from each vehicle is specified as the peak level measured during driveby at a standard distance (usually 50 feet). Noise at other points is computed as a function of distance between vehicle and observer. The Equivalent Level L_{eq} for all vehicles (see Section 2) is computed by adding the frequency weighted acoustic energy from all vehicles and averaging over

*All relative and absolute sound levels in dB are A-weighted levels unless otherwise specified.

time. This process is independent of the spacing between individual vehicles. Only average traffic density need be known. For multilane roadways, each lane is considered a separate source: it is an acoustic line source with strength proportional to the average peak passby level and to the traffic density. L_{eq} for the total highway traffic is computed by adding the acoustic energy from all lanes taking into account appropriate factors due to propagation (see Section 4.4).

The noise countermeasure effectiveness analysis of Chapter 8 requires that day and night be considered separately. It is assumed that, on an average, 87 percent of the traffic volume occurs during daytime and 13 percent at night.[S12, S5] Also, certain countermeasures are to be applied to heavy trucks only so that truck noise is separated from automobile noise which means that the percentage of heavy truck traffic must be known.

Peak passby levels of the untreated vehicles (both engine and tire noise combined) have been found to obey the following speed-dependent relations for nominal California traffic conditions:[S12]

$$L_{auto} = 73 + 30 \log_{10} \frac{V}{65 \text{ mph}} \quad \text{in dB} \tag{4-1}$$

$$L_{truck} = 83 + 26 \log_{10} \frac{V}{65 \text{ mph}} \quad \text{in dB} \tag{4-2}$$

A small correction is applied to the model to account for differences in motor vehicle noise regulations between California and Washington.*

For arterial roadways, the simulation program computes L_{eq} at 50 feet based on the above expressions and the average daily traffic, number of lanes, median width, and percentage of heavy trucks. Based on observations on arterials in California, automobiles and trucks are assigned different typical speeds on each lane of 2 and 4 lane arterials.[S12] The values assigned range from 20 to 30 mph for trucks and 25 to

*For Washington, 1.5 dB is added to the L_{eq} for autos and 2 dB for trucks.

30 mph for automobiles, depending on the particular lane and total number of lanes in the arterial. At these speeds, tire noise is not considered dominant so that tire noise countermeasures are not considered. The engine/exhaust noise reduction countermeasures considered for speeds less than 35 mph are then applied as reductions to the total noise levels indicated by Eqs. (4-1) and (4-2).

For the freeway through Spokane (U.S. Interstate 90), and several high-speed arterials for which the speed limits exceed 35 mph, tire noise is separated out so that engine/exhaust and tire noise sources are defined as follows:

Automobiles

Engine/Exhaust Noise = L_{eq} at 35 mph (Eq. (4-1)) + 4 dB

Tire Noise = L_{eq} at 35 mph (Eq. (4-1)) + 6 dB

Trucks

Engine/Exhaust Noise = L_{eq} at 35 mph (Eq. (4-2))

Tire Noise = L_{eq} at 35 mph (Eq. (4-2)) + 5 dB

In this way, tire noise countermeasures may be treated separately. Thus, a freeway is considered equivalent to a high-speed arterial without tire noise, plus a high-speed highway with tire noise only. Again, L_{eq} is obtained separately for automobiles, trucks, day and night.

Noise from local traffic is also considered a separate source. Local traffic is defined as traffic on collector and local streets in residential areas. The noise level calculation procedure first determines a base level for the entire community based upon reported annual mileage driven on these local streets. Based on the hypothesis that local traffic noise increases with population density, the noise level at a particular location is determined by weighing the base level by the local population density.[G8] The base level is obtained by computing the average number of daily passbys anywhere in the community, assuming again an 87–13 percent day-night split of traffic volume, a home set back 50 feet from the street, and a mean energy average (L_{eq}) per vehicle passby at 50 feet of 68.5 dB. This results in a base level for daytime and one for nighttime for local traffic which is applicable only to the traffic and population density of Spokane, Washington.

4.1.2 Buses

Buses are considered an important separate noise source in the central business district of the community under consideration. In order to obtain the average single event equivalent level for a bus passby at 50 feet, it is assumed: that half the time is spent accelerating, and half the time is spent decelerating; that acceleration produces a noise level of 80 dB; that deceleration produces a noise level equal to the noise level of the cruise speed from which deceleration occurs; that the average speed of the accelerating passby is 20 mph.[O2] This results in an average single event equivalent level of 84.2 dB. The number of passbys N past a particular location can be determined from bus schedules for daytime and nighttime. Then, at 50 feet:

$$L_{eq_{day}} \simeq 84.2 + 10 \log N_{day} - 47.3 \text{ in dB} \qquad (4\text{-}3)$$

$$L_{eq_{night}} \simeq 84.2 + 10 \log_{night} - 45.1 \text{ in dB} \qquad (4\text{-}4)$$

4.2 RAILROADS

Noise levels generated by railroad on-line operations (other railroad sources such as switching yards are considered part of industrial areas) are computed using data compiled in Reference S11. The following Single Event Noise Exposure Levels (SENELs) are typical for train speeds around 30 mph:

Locomotive – 102 dB at 100 feet
Freight Cars – 98 dB at 100 feet
Passenger Cars – 87 dB at 100 feet

Based upon typical operations in the Spokane area, an average length for freight trains of 3100 feet is used while 850 feet is typical of passenger trains. Locomotives are treated as separate noise sources because of their characteristics which are very different from those of railway cars. The number of operations N can be obtained from schedules, again separated into daytime and nighttime. The equivalent levels at 100 feet then obtain from:

$$L_{eq_{day}} = \text{SENEL} + 10 \log N - 47.3 \quad (4\text{-}5)$$

$$L_{eq_{night}} = \text{SENEL} + 10 \log N - 45.1 \quad (4\text{-}6)$$

4.3 AIRCRAFT

Aircraft noise exposure and countermeasure analysis is conducted through use of a Wyle-developed computer model.[B1] The analysis of aircraft noise exposure begins with the specification of the "airport system" parameters:

- The endpoints of each runway used
- The airport pressure altitude and mean temperature
- The ground tracks followed by all aircraft, both arriving and departing
- Altitude, thrust level, and velocity versus distance profile data for each approach track

- Takeoff altitude restrictions and power cutbacks, if any
- The number of daily flights, divided into night and day operations, for every significant combination of aircraft type and ground track (note that the same aircraft with a different weight will be considered a distinct aircraft type)

In addition, the following aircraft dependent data are required:

- Noise versus distance for several thrust levels
- Altitude, thrust, and velocity versus distance from brake release for takeoffs

Given all the above data, the noise level at a point caused by a single flight can be determined. First, the ground track is examined to determine the point of closest approach. This defines the distance of the aircraft from touchdown or liftoff which in turn determines its altitude, thrust, and speed. Using the altitude, the slant range is determined. The noise level in EPNdB is found by interpolating in a table of EPNdB versus distance. Corrections for ground attenuation, shielding, and velocity effects are applied resulting in the noise level due to this flight. The Wyle program determines the total NEF at the point under consideration, by repeating the above procedure for every flight and summing logarithmically. Separate NEF values for daytime and nighttime are obtained. These are converted to L_{eq} using the approximate relations:

$$L_{eq_{day}} = \text{NEF} + 36.7 \qquad (4\text{-}7)$$

$$L_{eq_{night}} = \text{NEF} + 38.9 \qquad (4\text{-}8)$$

It is apparent from the above discussion that it is relatively straightforward to compute different NEF values for different aircraft noise countermeasures as for example:

- Rerouting of commercial aircraft over modified flight tracks;
- Simulation of quiet nacelle retrofit on existing aircraft;

- Segmented takeoff and approach paths;
- Night curfew.

Section 6.6 discusses the aircraft noise countermeasures which are feasible by the year 1978. Section 7.8 determines the associated costs. In Chapter 8, the countermeasures are examined as to their cost-effectiveness in community noise reduction in the context of the noise emitted from all sources.

4.4 SOUND PROPAGATION

4.4.1 Introduction

The evaluation of cost-effective strategies to reduce community noise involves the careful application of valid models for propagation of outdoor noise in urban areas. This section reviews the background on urban noise propagation and presents the specific propagation models applied to this study.

It is convenient to divide the various sound propagation effects into two categories: (1) fixed or stable effects which can be accounted for, and (2) variable or unstable effects which cannot be reliably accounted for. The finer breakdown of these two groups is as follows:

Stable (Predictable) Effects

Uniform Spreading Losses

- Point sources, loss varies as $1/R^2$
- Line sources, loss varies as $1/R$
- Planar (area) sources, loss varies from 0 to $1/R^2$

Nonuniform Spreading Losses

- Reflection by ground, buildings and other obstacles
- Diffraction by buildings and obstacles

Absorption Losses

- Absorption by ground and normal ground cover
- Atmospheric absorption (predictable for ordinary still air)

Unstable (Unpredictable) Effects

Nonuniform Spreading Losses

- Refraction by nonuniform atmosphere, winds, etc.
- Diffraction or scattering by turbulence, dust, or fog

Absorption Losses

- Absorption by an atypical ground cover (snow)
- Atmospheric absorption by dust or fog

The unstable sound propagation effects are considered "unpredictable" from a practical viewpoint due to their dominant dependence on weather. Ignoring these weather-sensitive propagation effects does not invalidate the study since the weather-induced variations will tend to be random in nature and, over a long period of time, average out to zero. While weather also has a significant influence on the "predictable" atmospheric absorption losses, the variation is not large for the significant sources of urban noise. That is, "standard day" weather conditions can be assumed to define the average absorption loss effects with reasonable accuracy. The following reviews the "predictable" propagation loss effects in more detail, including the most difficult problem of noise propagation in urban areas.

4.4.2 Uniform Spreading Losses

The apparent loss in acoustic intensity as the sound power radiated by a given source spreads out over an ever-increasing sound wave front area is conveniently called uniform spreading loss. Uniform, in this case, implies that the atmosphere is still and homogeneous so that the sound intensity decays in the ideal manner illustrated in Figure 4.4-1 for point, line, and area sources corresponding, for example, to a single vehicle, a stream of traffic on a single highway, and to a large industrial plant, respectively.

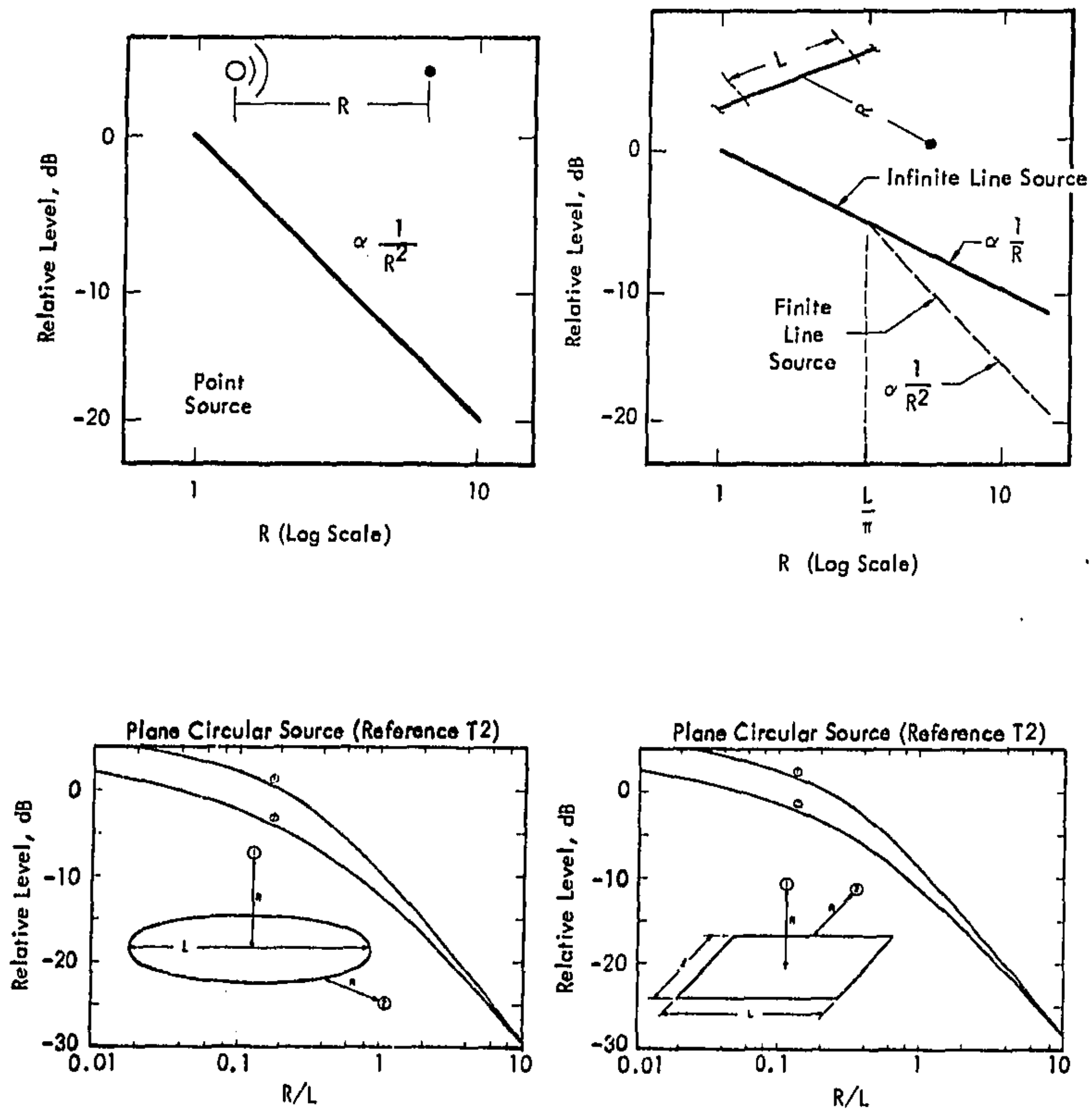

Figure 4.4-1. Uniform Spreading Losses from Point, Line, and Planar Sources

4.4.3 Propagation Losses Due to Air and Ground Absorption

- Air Absorption Only

Several fundamental mechanisms cause sound to lose energy at a constant rate, expressed in terms of dB/unit distance, as it propagates through the air.[S9] This absorption loss is a fundamental element in limiting the residual noise generated by all distant (nonlocal) sources. Based on Shaw and Olson's model for residual noise level in a uniform distribution of random sources, the effect of the absorption loss rate on the relative residual noise level, in the plane of the sources, as a function of source density is shown in Figure 4.4-2.[S1] "Excess attenuation" means attenuation in excess of the uniform spreading loss.

For high-density, high-rise apartment areas, propagation of noise in the vertical direction must be considered. An analytical model for this case, based on the sound level above an infinite plane of uniformly distributed random sources, was recently derived by Sutherland[S10] based on an earlier urban noise model by Shaw and Olson.[S1] Figure 4.4-3 shows that this model predicts that, for a reasonable value of air absorption, the residual noise level above the ground will tend to fall off very slowly with elevation while the level of a typical "local" source will tend to decrease nearly as the inverse square law as elevation above the ground increases. This theoretical trend has been verified experimentally.[S10]

- Combined Air and Ground Absorption

The calculated effect of air and ground absorption losses on propagation over open flat terrain of maximum passby noise levels from a single automobile or heavy truck is shown in Figure 4.4-4. The frequency spectra used for these calculations are based on average values from Reference O2. Beyond a distance of about 100 feet, the added loss due to air and ground absorption, over that due to uniform spreading alone, is apparent. The ground absorption loss in Figure 4.4-4 is estimated for open flat terrain according to an empirical method.[S2]

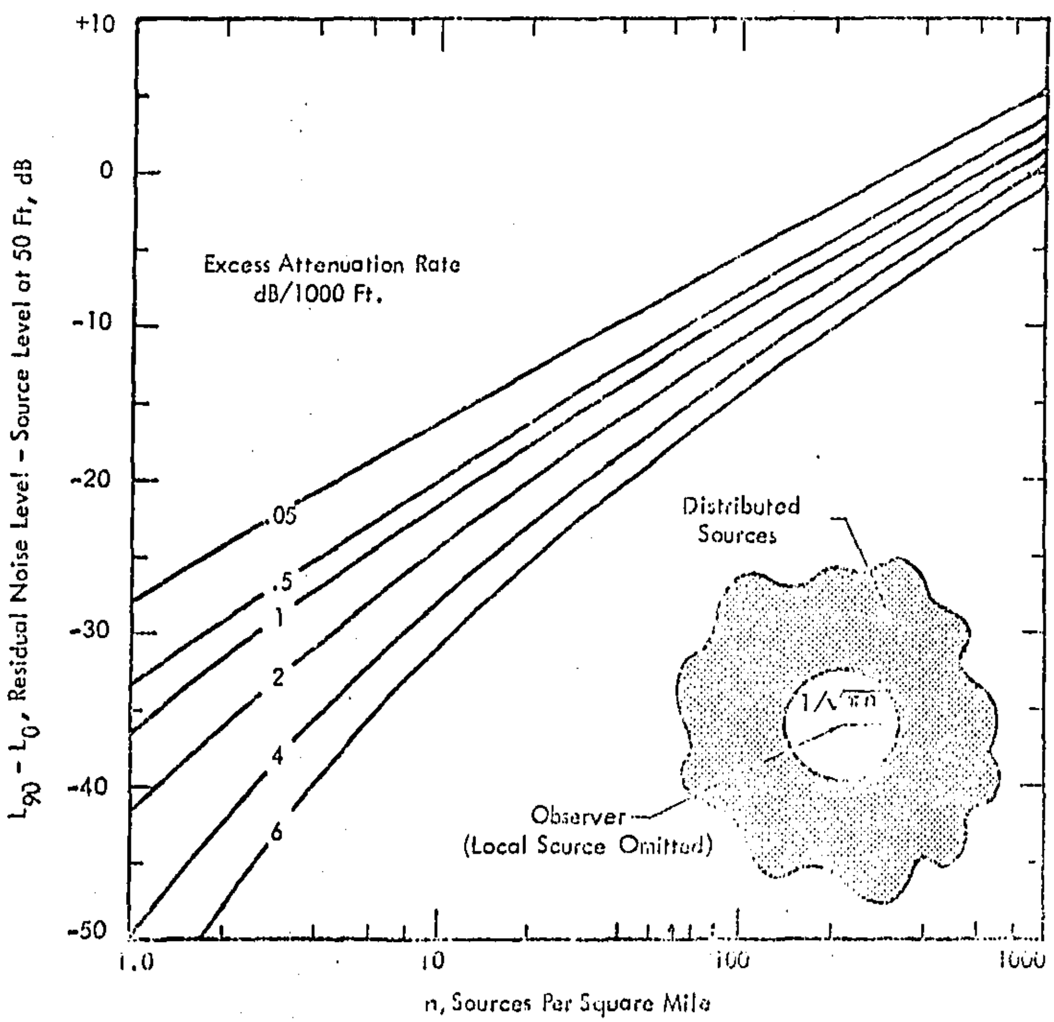

Figure 4.4-2. Residual Noise Level Relative to Source Noise Level at 50 Feet Without Shielding Loss (Adopted from Reference S1)

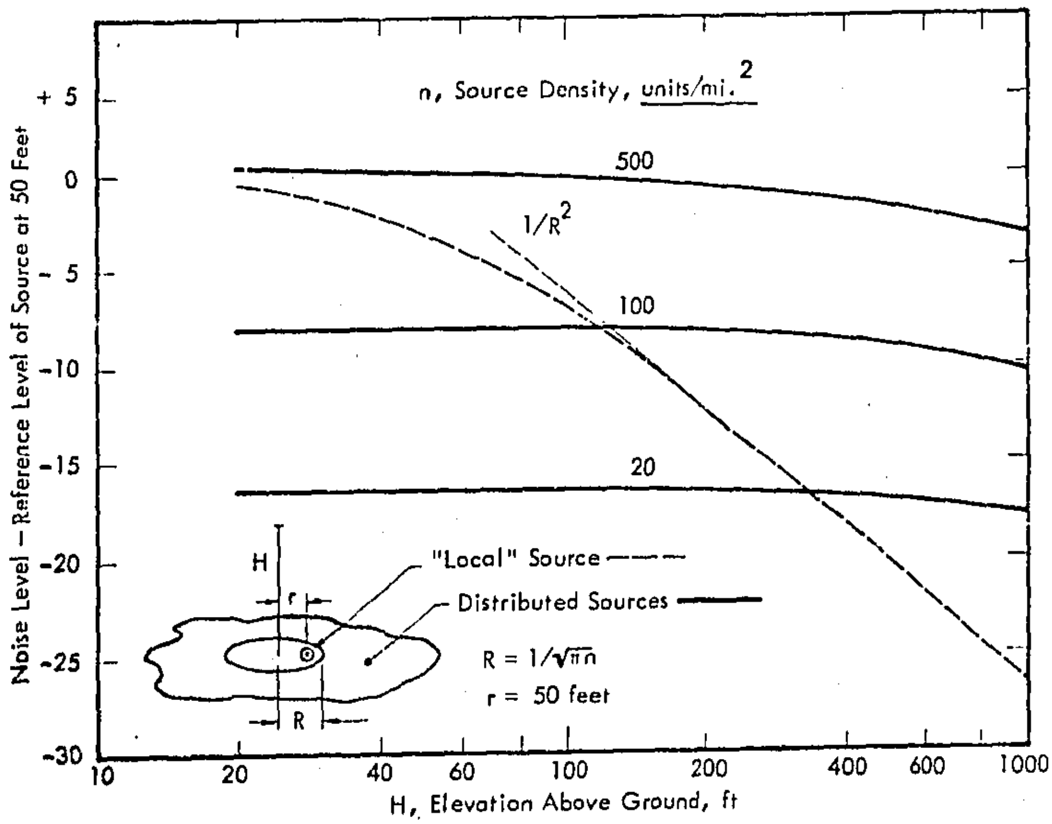

Figure 4.4-3. Computed Variation with Elevation of Ambient Noise Level (Solid Lines) from Uniformly Distributed Equal Random Sources of Varying Density in Ground Plane and Variation in Maximum Noise Level (Dashed Line) of "Local" Source Located 50 Feet from Base of Vertical Observation Line. All Levels Relative to Constant Reference Level of Each Source at 50 Feet. Atmospheric Absorption Coefficient Assumed Equal to 0.5 dB/1000 Feet.

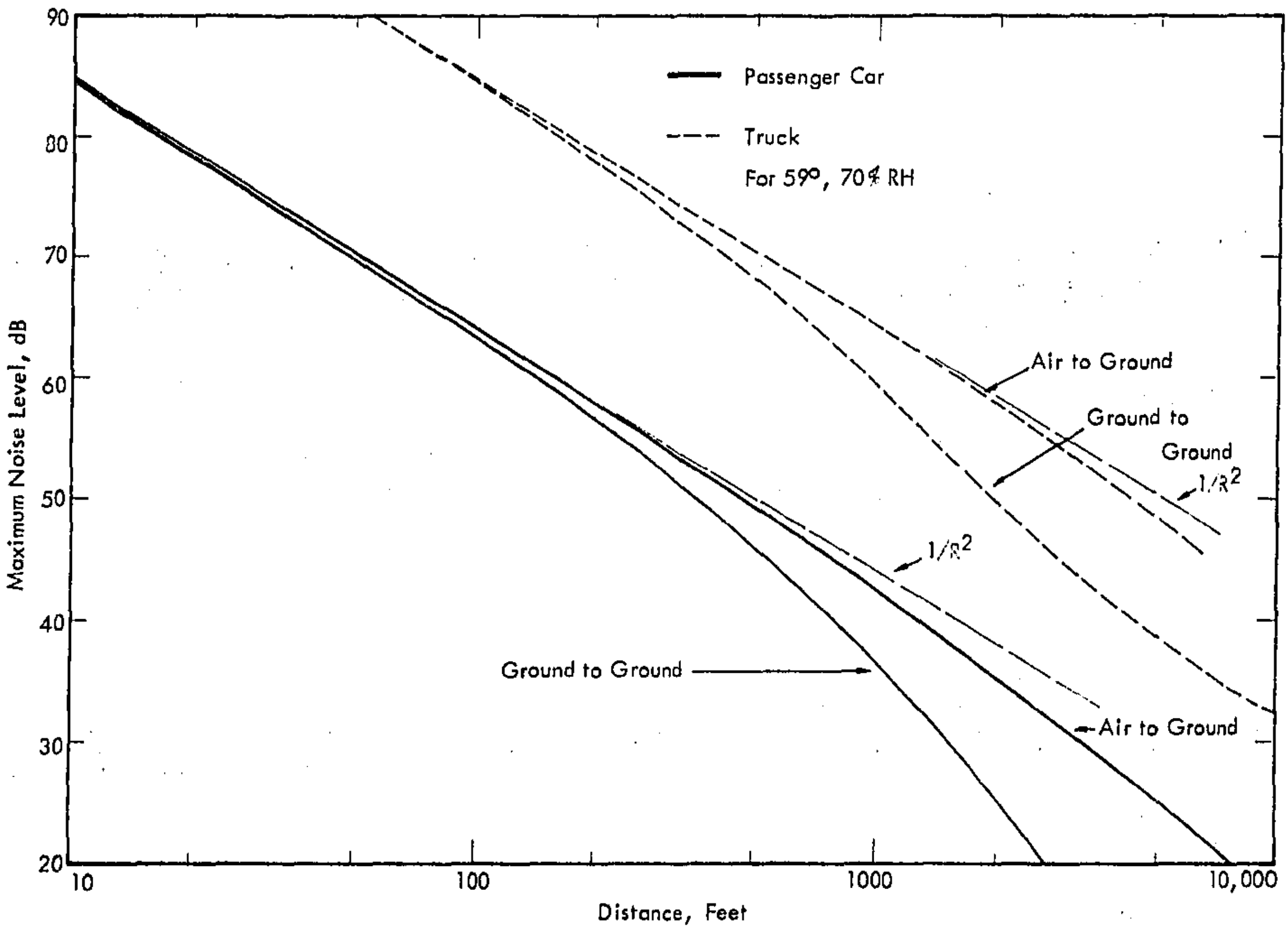

Figure 4.4-4. Typical Maximum Noise Levels with Distance for Highway Vehicles

4.4.4 Nonuniform Spreading Loss in Urban Areas

When the sound propagation path is no longer flat and open, prediction of the change in spreading loss becomes much more difficult. A conceptual model has been developed to handle the wide range of situations which can occur, i.e., a single isolated barrier or hill, or a cluster of commercial buildings. The model, illustrated in Figure 4.4-5, is based on describing the obstruction normal to the sound propagation path by a two-dimensional matrix with building height as the vertical axis and building open space ratio (or blockage) as the horizontal dimension. This allows an "obstacle" normal to the sound path to take any general configuration from completely open space to fully blocked with all practical gradations in between. A third (depth) dimension is added so that the actual propagation loss can be related to the distance along the propagation path. This simple three-variable model is nothing more than a useful organizer of propagation conditions. However, it is just this simple "organization" which is needed to provide a unified framework for defining propagation conditions in urban areas.

This approach also provides a quantitative foundation for describing unique land areas or cells by their acoustic geography. Thus, a given urban area can be broken down into cells according to the type of sound propagation characteristics appropriately described by a position on the three-dimensional propagation matrix. Appendix C contains more details on propagation modeling and cell definition.

4.5 FORMULATION OF L_{eq} FROM ALL SOURCES

In the Wyle noise exposure model, the community is described by a large number of population cells (see Appendix C, Section C.3.1). Each cell is assumed acoustically homogeneous, that is, of constant "acoustic geography." For one particular time (day or night) L_{eq} is calculated at a central point of each cell taking into account the noise from all sources and the propagation losses discussed in the previous section. The addition of the component L_{eq}'s is performed according to Eq. (2-5) to yield the total noise exposure from all sources at each cell.

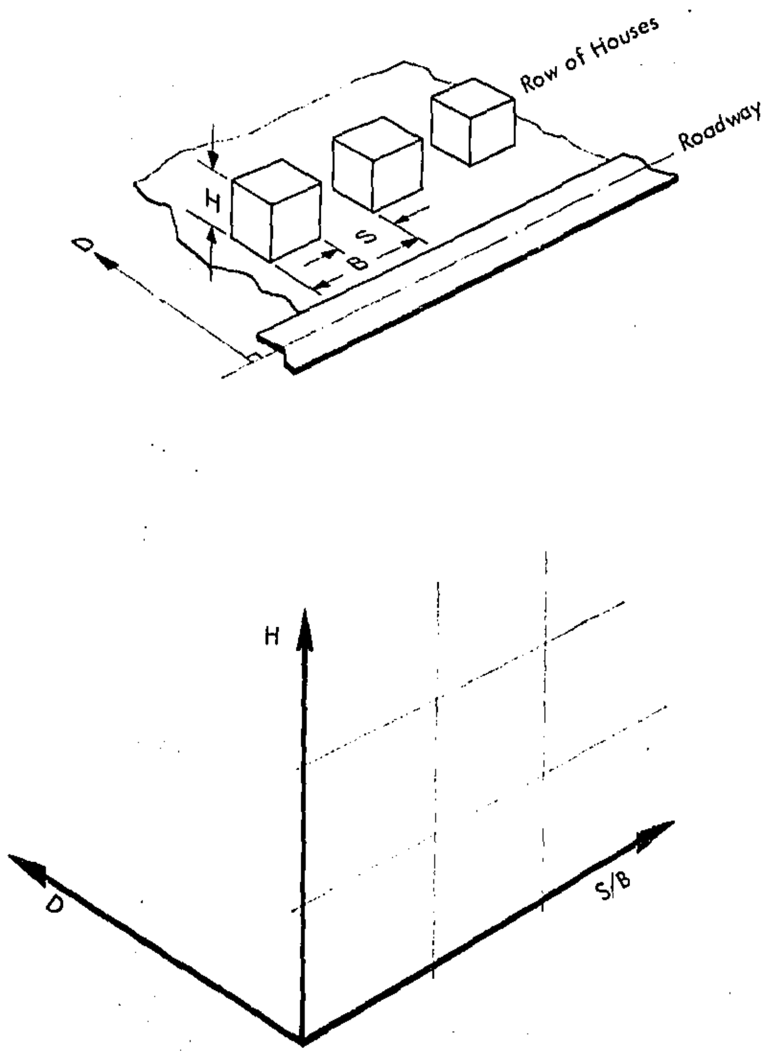

Figure 4.4-5. Simple Three-Variable Model for Excess Attenuation Values for Sound Propagation Through Urban Areas. Variables are: H = Building Height, S/B = Open Space Ratio, D = Depth or Distance Along Propagation Path.

Although all of the noise environments utilized for this study were computed, the prediction methods are based on an extensive experimental data base collected by Wyle and others over the past in a large number of environmental programs which required experimental verification. While such verification effort was desirable for this program, it was not feasible within the scope of the program resources. The basic trends developed by the predicted levels are still considered valid within the assumptions made for the overall study.

CHAPTER 5

QUANTIFICATION OF TRANSPORTATION NOISE USING L_{NP}*

In Chapter 2, it is shown that the Noise Pollution Level L_{NP} may be a better predictor of human response to noise than the Energy Equivalent Level L_{eq}. L_{NP} takes into account not only the total energy of exposure but also the variability of the noise level. To determine the L_{NP} from many noise sources requires that the complete statistical distribution function be known which makes the computation of L_{NP} much more complex. The general method of L_{NP} prediction at one point in the community consists of obtaining first the distribution of noise levels from each source, then combining these to form the distribution from all sources, and finally computing L_{NP} from the latter. These steps will now be described in detail.

5.1 SOURCE CUMULATIVE DISTRIBUTION FUNCTIONS

5.1.1 Road Traffic

Kurze has described the statistics of road traffic noise using a theory which is mathematically very involved and difficult to apply to a practical situation.[K7, K5] In a subsequent paper,[K4] Kurze presents approximate methods for obtaining the cumulative distribution function for points close to the roadway: i.e., the product $M = \lambda d$ must be small, where λ is the vehicle density (number of vehicles per unit distance), and d is the perpendicular distance of the observer from the roadway. The cumulative distribution function then is:

$$P(\Delta L) = \mathrm{erf}\left(\sqrt{M}\ 10^{-\Delta L/20}\left[1 - \frac{64}{9\pi}\ \frac{M\,10^{\Delta L/10}}{(1+2M)^2}\right]\right) \qquad (5\text{-}1)$$

with $\Delta L = L - L_{eq}$, $M = \lambda_{eq} d$.

*All relative and absolute sound levels in dB are A-weighted levels unless otherwise specified.

Furthermore,

λ_s is the vehicle density of the s^{th} class of vehicles;

$L_{ref,\,s}$ is a reference noise level from a vehicle in the s^{th} class of vehicles, measured at a distance r_o from the roadway.

Then,

$$L_{eq} = 10 \log \left[\sum_s 10^{L_{ref,\,s}/10} \frac{r_o^2}{d} \lambda_s \pi \right] \tag{5-2}$$

$$\lambda_{eq} = \frac{\left(\sum_s \lambda_s 10^{L_{ref,\,s}/20} \right)^2}{\sum_s \lambda_s 10^{L_{ref,\,s}/10}} \tag{5-3}$$

Equation (5-1) is applied twice: once for the total traffic mix, and again only for the noisiest class of vehicles. The two distribution functions are then combined graphically as shown in the example in Figure 5.1-1. Kurze does not state up to what value of M Eq. (5-1) is valid. However, an upper practical limit seems to be $M \approx 0.5$. Above this value the $\sqrt{M}$ -term begins to dominate and the distribution curve starts to wander off unreasonably to the right (Figure 5.1-2). In the cases considered in the present study, M is always less than 0.5 (see Chapter 8). However, it is conceivable that M does not always stay small if it is desired to take into account all relevant noises even from distant roadways. Also, the vehicle density λ may become large in urban areas, particularly when multilane highways are lumped into one acoustic source.

5.1.2 Railroads

Only noise from trains on railroad lines is considered in the Spokane analysis (i.e., no switching yard noise). A train passby is assumed to be at constant speed. The distance from the track of the point where L_{NP} is to be evaluated gives the peak

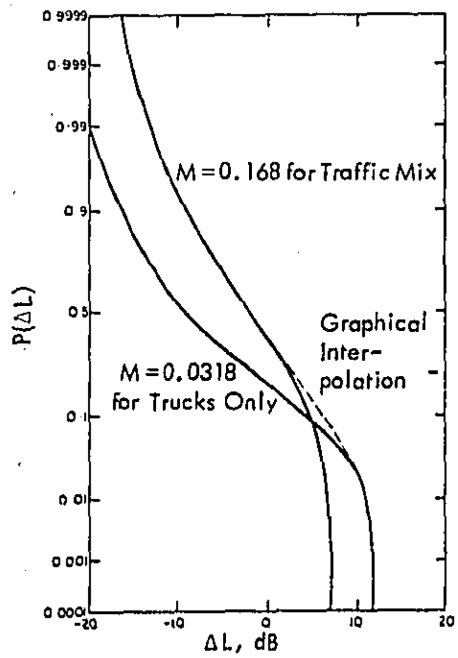

Figure 5.1-1. Example for the Construction of a Cumulative Distribution Function for Noise from Mixed Traffic by Means of Graphical Interpolation. Considered is a Traffic Mix with 10 Percent Heavy Trucks, which are Noisier by 15 dB than the 90 Percent Passenger Cars (from Reference K4). M = Number of Vehicles Per Unit Distance Times Perpendicular Distance from Observer to Roadway.

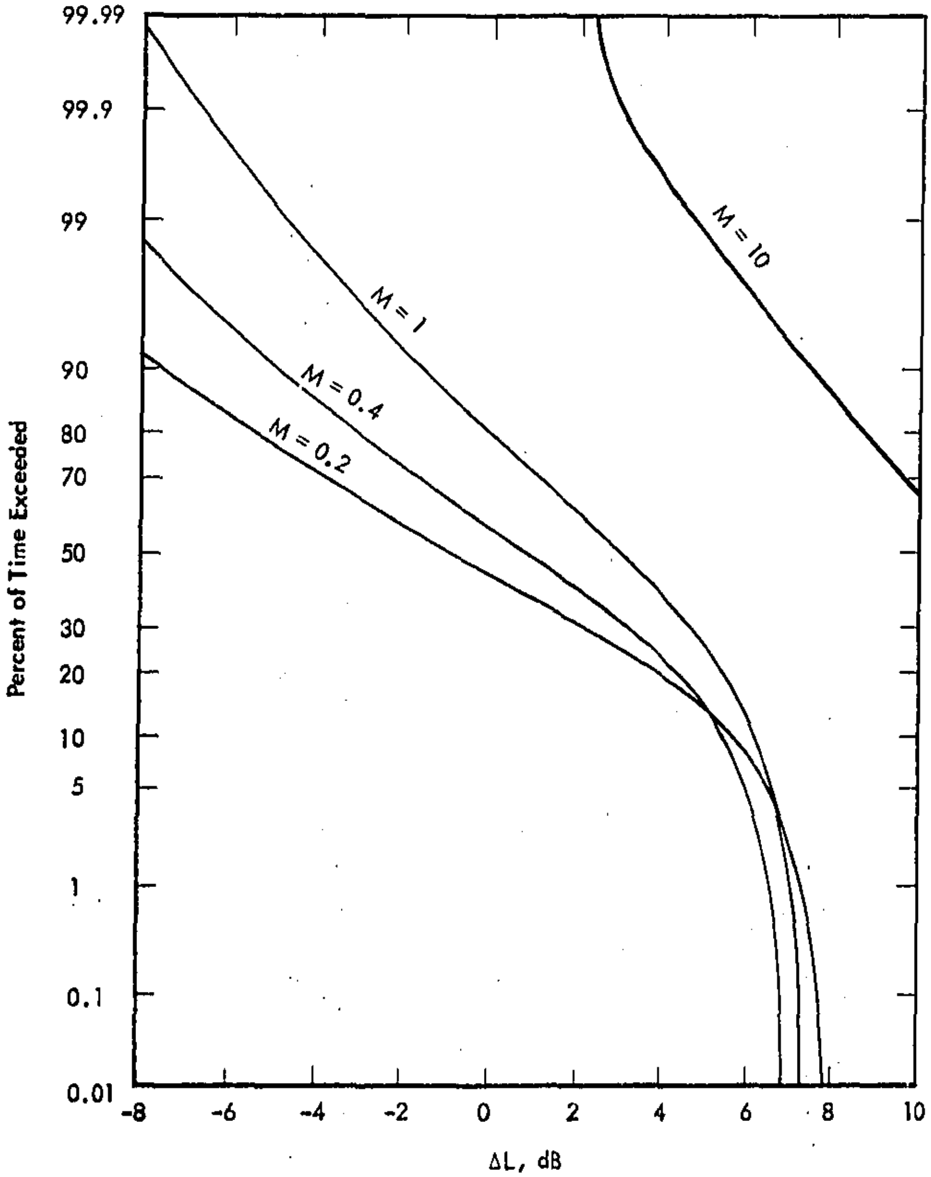

Figure 5.1-2. Cumulative Distribution Functions of Traffic Noise as Obtained by Eq. (5-1) with Parameter M (Vehicle Density Times Distance) Varying.

level of the locomotive; distance and speed give the level generated by the cars.[S11] Graphically, a train passby is represented as in Figure 5.1-3. Knowing the characteristics of train traffic for day and for night, the cumulative distributions of levels can easily be synthesized.

5.1.3 Aircraft

The noise level time history of an aircraft fly-past is approximated by that of a moving dipole oriented at 45 degrees to the direction of travel (Figure 5.1-4). The lower lobe of the figure-8 directivity pattern of the dipole approximates the directivity of jet exhaust noise. Given the maximum level, the aircraft velocity and the distance to the flight track, the noise level time history can be computed. The total air traffic is categorized into aircraft classes (four for the Spokane analysis) with characteristic noise levels and flight speeds. Together with aircraft movement statistics, the cumulative statistical distribution function for each class can be computed for the daytime and the nighttime. The distributions of each class are combined using the method described in Section 5.2.

5.2 COMBINED CUMULATIVE DISTRIBUTION FUNCTION

Section 5.1 describes how the distribution of levels from each source is obtained. This section presents the method used to combine the source distributions into the distribution of noise levels at the point where L_{NP} is to be calculated. Nelson has described three methods of statistically combining noise from separate time-varying sources:[N3]

- The first method is exact in the sense that it obtains the probability of the occurrence of a certain level from probability products of the component distributions. To execute this would be too time-consuming an operation.
- The second method is an approximation and uses Eq. (7) on Figure 5.2-1. A(L) and B(L) are the probabilities that noise level L is

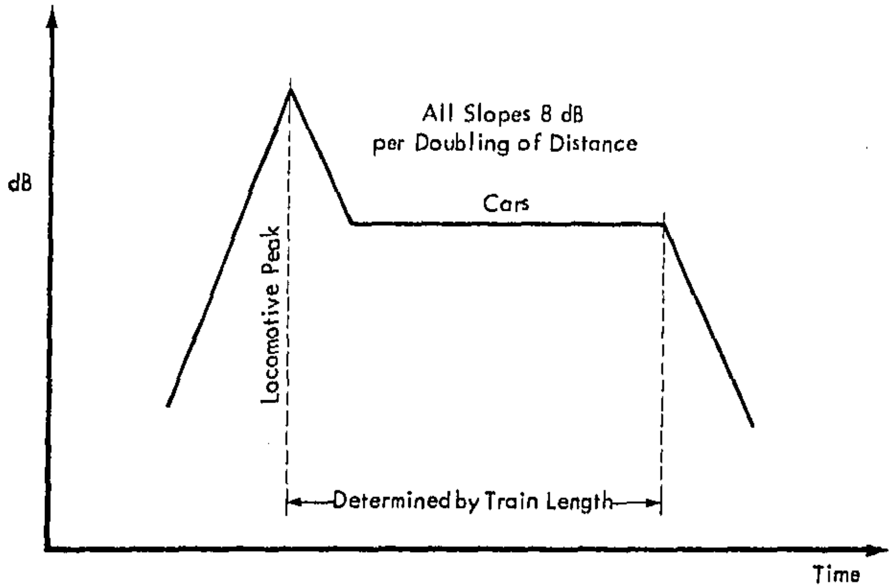

Figure 5.1-3 Simplified Noise Level Time History of a Train Passby. Slope of 8 dB per Doubling of Distance Consists of 6 dB for Uniform Spreading Plus 2 dB for Excess Attenuation Due to Ground, etc.

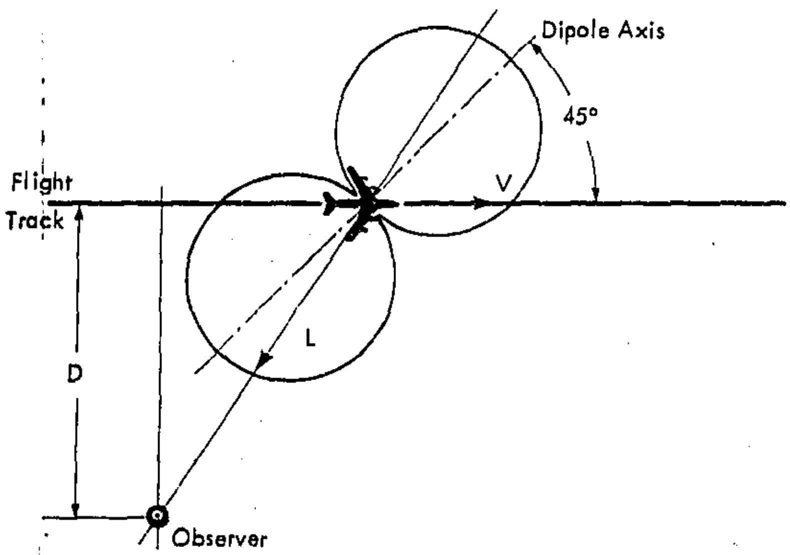

Figure 5.1-4. Simple Model for Obtaining Noise Level Time History of a Jet Aircraft Fly-Past Using a Convecting Dipole. D = Distance (Slant Range), V = Velocity, L = Noise Level

is exceeded for sources A and B, respectively. The result is the combined cumulative distribution C(L). This method is sufficiently accurate if only two distributions are combined.

- The third method should be used if there are three or more component distributions; then, the more exact Eq. (8) on Figure 5.2-1 should be applied in succession. This is the method used in the present work with a Wyle-developed computer program which can combine up to six distributions at one time.

$$C(L) = 0{\cdot}7[A(L) + B(L) - A(L)B(L-3) - B(L)A(L-3)] + 0{\cdot}4A(L-3)B(L-3) + 0{\cdot}3[A(L-3) + B(L-3)] \quad (7)$$

$$\begin{aligned} C(L) = {} & A(L) - A(L)\,.\,B(L-3) + A(L-3)\,.\,B(L-3) - A(L-3)\,.\,B(L) \\ & + B(L) + [A(L-2) - A(L)][0{\cdot}3B(L-5) + 0{\cdot}7B(L-4) - B(L-3)] \\ & + [B(L-2) - B(L)][0{\cdot}3A(L-5) + 0{\cdot}7A(L-4) - A(L-3)] \\ & + [A(L-2) - A(L-1)] \\ & \times [0{\cdot}18B(L-7) + 0{\cdot}42B(L-6) + 0{\cdot}1B(L-5) - 0{\cdot}7B(L-4)] \\ & + [B(L-2) - B(L-1)] \\ & \times [0{\cdot}18A(L-7) + 0{\cdot}42A(L-6) + 0{\cdot}1A(L-5) - 0{\cdot}7A(L-4)] \\ & + [A(L-3) - A(L-2)][0{\cdot}15B(L-5) + 0{\cdot}35B(L-4) - 0{\cdot}5B(L-3)] \\ & + [B(L-3) - B(L-2)][0{\cdot}15B(L-5) + 0{\cdot}35A(L-4) - 0{\cdot}5A(L-3)] \\ & + [A(L-1) - A(L)] \\ & \times [0{\cdot}1 + 0{\cdot}2B(L-13) + 0{\cdot}2B(L-10) + 0{\cdot}2B(L-9) + 0{\cdot}2B(L-8) \\ & + 0{\cdot}09B(L-7) + 0{\cdot}01B(L-6) - 0{\cdot}3B(L-5) - 0{\cdot}7B(L-4)] \\ & + [B(L-1) - B(L)][0{\cdot}1 + 0{\cdot}2A(L-13) + 0{\cdot}2A(L-10) + 0{\cdot}2A(L-9) \\ & + 0{\cdot}2A(L-8) + 0{\cdot}09A(L-7) + 0{\cdot}01A(L-6) \\ & - 0{\cdot}3A(L-5) - 0{\cdot}7A(L-4)] \quad (8) \end{aligned}$$

Figure 5.2-1. Formulas for Combining Two Noise Level Distribution Functions (From Reference N3). The Cumulative Distribution Function C(L) is Intended to Represent the Summation of all Possible Simultaneous Combinations of Levels from Sources A and B which Add Up on an Energy Basis to the Desired Level L. These Component Levels are Weighted by Their Respective Probability of Occurrence. Eq. (7) is Simply a Less Accurate Approximation of This Process.

5.3 COMPUTATION OF L_{NP}

The Energy Equivalent Level L_{eq} and the standard deviation σ of the combined distribution are computed via computer program. Then, from Section 2.3:

$$L_{NP} = L_{eq} + 2.56\,\sigma \tag{5-4}$$

CHAPTER 6

COUNTERMEASURE NOISE REDUCTION ANALYSIS*

6.1 INTRODUCTION

The following sections present individual discussions on the technical feasibility of accomplishing varying degrees of noise reduction for the time period 1973-1978 for the major sources of environmental noise utilized in the Spokane, Washington analysis. The dominant noise sources considered in the analysis are:

- Heavy trucks (above 10,000 lbs)
- Automobiles
- City buses (central business district only)
- Railroad operations (on-line freight and passenger movements only)
- Commercial aircraft

The general treatment of the analysis includes a definition of the major noise producing subcomponents for each source and the extent to which feasible noise reduction can be accomplished, either through new product modifications or existing "fleet" retrofit, by 1978. Different modes of operation are considered and different degrees of noise reduction are predicted for the various modes of individual source operation. The methods of noise reduction consider, where appropriate, not only physical source modifications which account for the net noise reduction of all source components but operational modifications affecting the individual and the composite fleet or stream as well.

Modifications or adjustments to the path between source and receiver in the forms of source rerouting, construction of intervening noise barriers and receiver relocation out of the proximity of the source are also treated. In addition, a discussion is presented on the topic of improvement of outdoor to indoor sound insulation in dwellings (both commercial and residential).

*All relative and absolute sound levels in dB are A-weighted levels unless otherwise specified.

Specific countermeasures are not defined or developed for "receiver-controlled" sources of environmental noise (household appliances, home and commercial power tools, etc.) as the primary goal of this program is to assess cost-effective means of reducing external environmental noise.

In addition to the environmental noise sources discussed in this section, three other categories of external sources were considered in the preliminary research of this program, although they were not utilized in the Spokane analysis. These sources were:

- Stationary noise sources — industrial plants
- Building construction operations
- Rapid transit systems

For completeness in this presentation of the work effort, and to allow future expansion of the scope of the study, a summary of the technical feasibility of achieving defined levels of noise reduction for these three sources, along with summary economic considerations for rapid transit, is presented in Appendix F. The data in this chapter was obtained from References G4, F1, G3, F6, W6, and U9.

6.1.1 Motor Vehicle Retrofit

When considering the quieting of motor vehicle noise sources, a distinction must be made between modifications at the manufacturing level of new production units, and modifications in the field of already existing units. The latter is referred to as "retrofit." It should be noted that this definition of retrofit does not include the restoration of a vehicle to OEM (original equipment at manufacture). Consequently, the requirement that vehicles be left at or restored to OEM conditions is not considered as a means of noise source reduction in this study.

The sections below develop the technical feasibility of source modifications for both newly manufactured units and units requiring retrofit. The associated costs are taken from sources available as of September 1974. Whether or not the technically feasible modifications are also economically feasible is one of the results of the final analysis presented in Chapter 8.

For automobiles, it's fairly straightforward to develop retrofit source modifications required to achieve a certain noise level. Trucks, however, vary much more in their configurations so that it is difficult to determine across-the-board modifications. This problem is treated in Appendix G where the probable necessary retrofit changes are developed depending on the truck age and the desired maximum noise level. It is considered beyond the scope of this study to go into more detail than presented in Appendix G. In view of the general nature of the study, which takes into account many noise countermeasures other than those pertaining to motor vehicles, such an in-depth investigation does not appear necessary.

Insufficient data was available on the labor cost of installing the motor vehicle retrofit hardware in the field. One may expect that it will be more expensive to install a retrofit part in the field than on the assembly line. However, this need not always be the case. Since a retrofit period of 5 years is allowed, installing an improved muffler, for example, can be delayed until such time when the original component needs replacement anyway. Generally, it is assumed that the retrofit costs equal those of the incremental retail costs of manufacturing new motor vehicles. In order to demonstrate the sensitivity of the results of this study to this assumption, a substudy has been carried out. It is described in Sections 7.4.2 and 8.3.4.

6.2 HEAVY TRUCK SOURCES

Almost all heavy trucks (gasoline and diesel) are custom designs, although they are produced in high volume by large manufacturers. They are assembled of standard engine, powertrain, body, and auxiliary equipment components; however, the matrix of combinations for even relatively simple or low production models is excessive. The combination picked for the truck configuration is based upon the customer needs. Because of this concept, truck noise levels may vary from being exhaust noise-dominate to engine/mechanical or cooling fan noise-dominate. In order to assess which source requires reduction first, it is necessary to perform a noise source identification test; otherwise, the process of noise reduction becomes a matter of revising all major components and retesting. This concept presents a two-sided dilemma to the owner of trucks in the field, since he must choose between the cost of modifying all major noise sources or paying for the technical expertise of noise source identification. Thus, it is not practical to think in terms of a "typical" truck or even a series of typical designs. Rather, one must consider the range of components that are basic to most designs and assess noise reduction potential over this broad range. Hence, discussions of truck noise reduction are, of necessity, somewhat general. The scenarios of truck noise reduction developed are necessarily dated by assuming initial retrofit action started in 1974.

Throughout the treatment of noise reduction for trucks and all other highway vehicles considered, the absolute levels are based on design levels that would presumably be measured in standard SAE tests. Actual regulatory levels might be slightly higher to allow for measurement errors and manufacturing tolerance. However, as long as one consistent method is used throughout, the relative change in levels is still valid.

6.2.1 Exhaust Noise

While exhaust noise constitutes a major source, it is felt that this vehicle noise component, as has been demonstrated by industry, is readily amenable to treatment by the use of turbochargers and improved design mufflers to help in achieving an 86 dB vehicle (measured per SAE J366b). The next level of reduction in the range of 86 to 80 dB for the exhaust involves much higher expenditures on a dollar per dB reduction comparison. Muffler manufacturers have placed a heavy emphasis on new muffler systems for trucks which include larger mufflers, mufflers incorporating double wall construction to reduce noise emission from the shell, intermediate resonator chambers, and flow through fiberglass-packed extension stacks. They have published usage tables which recommend various muffler combinations to achieve approximate noise levels with specific engines. Upon application the manufacturer or owner must try these configurations on the particular model truck that is being revised. The results may or may not be as anticipated because of space limitations for positioning the muffler, resonator or extension stack in the system at the location recommended by the muffler manufacturer. This design location is based upon a frequency analysis and experimental testing of the exhaust from a particular engine. For the components to function properly, they must be placed the correct distance from the engine to correspond to the wavelength or increment of wavelength of the frequency component which they are designed to affect. If this is not possible, because of space limitations, the exhaust noise may increase rather than decrease.

The incremental retail cost of reducing exhaust noise of newly manufactured units to a range of 86 to 80 dB by new double wall mufflers and possible additions of resonators ranges from $40 to $80. Extension stacks are not production priced so that this price does not include them. This cost is for components only and does not reflect any additional cost which will be incurred as a result of more sophisticated clamps used with the new muffler system, installation costs, or noise and back pressure testing. The standard flexible piping on trucks must be replaced with more reliable and leak proof joints. As noise levels are reduced, any possible exhaust leaks will have a profound effect upon exhaust noise levels. A retrofit installation will cost the owner between $75 to $150 for parts plus installation and testing costs. Further improvements may be obtained by incorporation of manifold mufflers which, if optimally configured, may eliminate the need for additional downstream mufflers on some engines. An estimate based upon usage on one engine as a development item indicates an additional 6 dB exhaust noise reduction at a customer cost of approximately $100. For some truck configurations, there is a severe problem of installation clearances, particularly with V8 engines. The existing exhaust flanges and turbo installations are very close to the frame and the engine tunnels. The $100 figure is the cost of the manifold only (fleet price) and does not include matching piping required to adapt to an existing exhaust system on installation and test costs. Noise testing and engine back pressure testing may be required.

6.2.2 Engine Mechanical Noise

Reductions of the order of 5 to 8 dB (measured in a test cell at 3 feet, engine noise only) have been achieved with damped panels partially enclosing the engine. Panel applications to the final vehicle have resulted in overall reductions of 1 to 3 dB dependent upon the relative predominance of engine noise. Factory costs for these panels range from $100 to $150. Some panels, such as side panels showing reduction during engine testing, will not have the same positive effect on an overall vehicle installation because body panels may serve the same purpose.

Reductions of 5 to 8 dB in engine noise have been achieved with almost complete enclosures. Estimated manufacturing costs (excluding increased maintenance) have been reported at around $250 per vehicle. When enclosures are incorporated, it is necessary to be very cognizant of any harmful effects on the cooling system.

6.2.3 Engine Cooling Fan

Traditional approaches to this problem have largely consisted of increased radiator core sizes and use of larger (improved efficiency) fans turning at slower speeds. Fan noise reductions of up to 7 dB have been demonstrated with this method. More recently, emphasis has been on a complete cooling system redesign in addition to fan analysis.

Emphasis has been placed on improving cooling system efficiency by evaluating the following parameters:

- Fan design efficiency as a function of blade cross-section, number of blades, spacing of blades, area of blades, and blade projected width.
- Blade tip clearance from shroud.
- Shroud sealing at radiator and sealing adjacent to radiator to reduce air recirculation from fan blade tips.
- Positioning of fan in shroud.
- Positioning of fan relative to radiator.

- Proximity of pulleys and ancillary equipment to the fan.
- Evaluation of radiator configurations relative to fan air flow restriction and its effect on noise.
- Evaluation of air flow characteristics of fan in different engine compartments.
- Effect of noise shields upon cooling system air flow to determine if air-to-boil specification of factory is affected.
- Shroud design.

The concentrated effort by manufacturers in the cooling technology exemplifies the magnitude and impact of cooling system noise on heavy duty trucks.

Advanced concepts for truck cooling have been introduced by some suppliers which are rear mounted hydraulically driven fan cooling packages. The hydraulic package is thermal sensing and operates in a manner similar to the engine mounted thermatic and viscous fan drives. The more exotic systems are not applicable to the present day designs if usable space between the bumper to back of cab is to remain the same.

Other approaches which have developed include raising of the cab and moving the engine rearward. These more involved improvements may not be adaptable by all manufacturers.

The present cooling system effort is of concern to manufacturers on two counts: the upcoming noise levels that they must meet, and the now current marketing of higher horsepower engines by Detroit Diesel, Cummins, and Caterpillar which will require additional cooling.

To satisfy the present day design, several approaches are being pursued:

- Incorporate all possible changes on existing cooling system so basic envelope will not change. This would require a new type fan, new shroud design and new drive pulleys to slow the fan. At the factory, this would cost approximately $35. On the other hand, on a retrofit basis, this change might run as high as $250 for parts alone to a fleet operator. Additional costs would be incurred for installation of parts and testing of the vehicle.

- Increase size of radiator and put larger, slower turning fan on vehicle. This fix is only applicable on new trucks at the factory and not available to all manufacturers. The existing cab designs would not allow enough room for larger radiators on some cab-over-engine trucks and hoods would need rework on conventional trucks. There would be no retrofit value of this concept because it might necessitate body changes which would become very expensive for the owner of trucks already in the field. The benefits from this concept are that fan noise is greatly reduced, but a questionable area exists as to whether air-to-boil specifications are still being met since ram air is weighted very heavily in the design concept.

- Incorporate a flexible fan or a thermatically controlled "demand type" fan clutch. These systems have resulted in a fan noise reduction of 2 to 10 dB at factory costs ranging from $2 to $190 per vehicle. The flex fan is practical for use on high torque engines where the engine develops almost maximum BHP at an rpm lower than its maximum rated rpm. They are not applicable to a normal engine that achieves rated BHP at its rated rpm because the fan may be flattened out at that point and not be supplying adequate air flow. The thermal sensing clutches in most cases require a larger packaging envelope than the factory drive pulleys, so that they may not be applicable to a retrofit installation on older vehicles. On some vehicles, the use of thermal sensing clutch fans could preclude the use of radiator shutters if the truck was not subjected to severe cold conditions where temperature control could not be maintained by the thermostat alone. The elimination of shutters could save as much as $100 cost to the customer. The retrofit installation will not realize any cost saving since the price of the shutters would have been included with the cost of the vehicle. A saving of approximately 10 to 20 horsepower may be realized when using a thermal sensing clutch which is normally wasted by turning a fan when not required. It has been estimated that the fan is actually required only 10 percent of the engine running time.

Rather low cost figures are sometimes quoted for fan noise reduction because reductions are achieved by replacing just the fan blade in the field. These prices must be considered on the basis of what they are accomplishing.

The truck manufacturer is required to meet an air-to-boil specification dictated by the engine manufacturer. This must be met in order for the engine manufacturer to guarantee his engine. This air-to-boil specification is determined on a worst case situation in any area where that engine manufacturer sells his engines. In that manner, he is not caught in a distribution of his product based on an area matrix. This concept inherently adds a little overkill for some areas and some modes of operation.

The fleet operator is in a different situation: He knows the type of route and ambient temperatures to expect and amount of time required at full horsepower when maximum cooling is necessary. He may be able to change fans and actually lose part of the cooling potential, but not harm his operations.

6.2.4 Air Induction System

This source is not presently a problem area in that it is generally 10 dB below other major sources on an 86 dB truck. If an overall truck noise level of 80 dB is desired, then the intake system will probably have to be revised or the intake components and inlet duct relocated. The use of tuned intake systems can satisfactorily reduce intake levels. For retrofit vehicles in the field, the noise reduction techniques may not be readily available by repositioning intake piping and air cleaner. The system may have to be replaced for reducing overall truck noise from 86 dB to 80 dB on some vehicles. This field replacement would be approximately $50 customer costs in addition to installation and testing for noise and pressure drop.

It may be necessary to relax overall length restrictions on trucks and combinations (presently 65 feet in California) to accommodate some of the aforementioned modifications. These restrictions have necessitated short tractors to accommodate an economical payload. There is presently little uniformity between states for maximum size and weight limitations.

6.2.5 Truck Tire Noise

Analysis of low- and high-speed truck noise emission data indicates that at speeds above 40 mph, the tire component may clearly dominate the noise during passby. It has been found that reductions in the high-speed tire noise component on the order of 5 dB are possible by replacing crossbar design tires with rib design tires.[T3] Appendix G.3 provides further details including an analysis of the economics of this option.

To summarize the approach for defining truck noise reduction in this study, all of the truck noise sources are finally lumped together and treated as one noise source with an output which is essentially independent of speed. In the final results, this source is identified as "low-speed" truck noise (i.e., tire noise is not present). Countermeasures to abate this engine-generated noise are then lumped together for both the cost and effectiveness analysis of this source. For high-speed roadways (speeds from 35 to 55 mph), tire noise is then added to the engine-generated truck noise and reduction of this (high-speed) tire noise is treated separately from the engine-generated noise reduction.

6.2.6 Heavy Truck Noise Reduction Scenarios

Given the assumption of a one-to-one relationship between noise reduction as indicated by the SAE J366b test procedure and actual observed noise emission characteristics of heavy trucks at speeds less than 35 mph (see Appendix E), we may now proceed to define a series of new production and retrofit combinations which yield various overall 1978 fleet low-speed noise reductions for various levels of total cost. A definition of the analysis cases assumed follows and is illustrated in Figure 6.2-1. The analysis of costs to achieve these levels is given in Section 7.5.

The specific cases analyzed are summarized as follows:

Case 1 - New production at 86 dB (SAE J366b) through 1978, no retrofit of existing fleet.

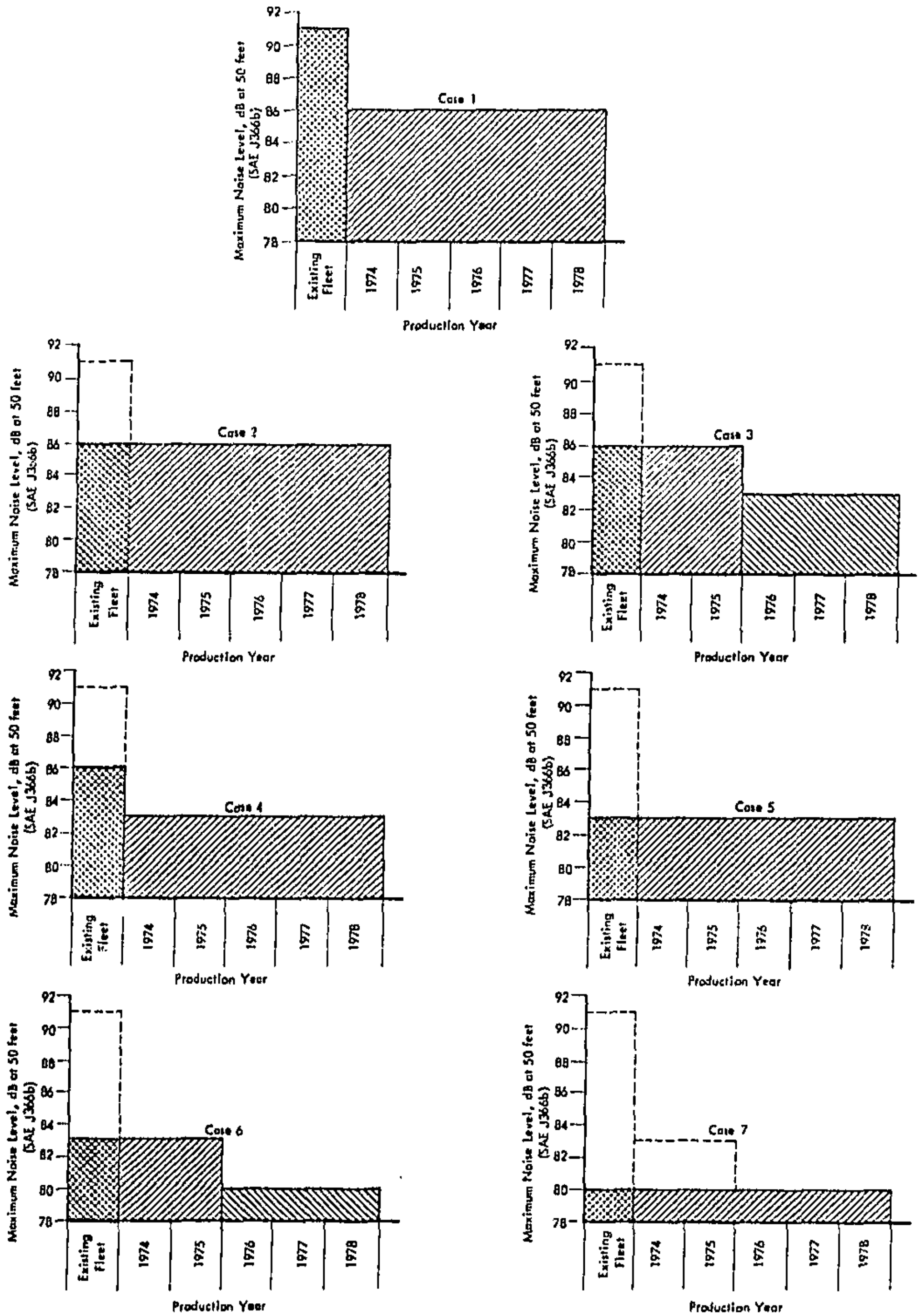

Figure 6.2-1. Scenarios of Truck Noise Reduction

Case 2 - New production at 86 dB through 1978, retrofit existing fleet to 86 dB.

Case 3 - 1974 and 1975 production at 86 dB followed by production at 83 dB through 1978. Retrofit of existing fleet to 86 dB.

Case 4 - New production at 83 dB through 1978, retrofit of existing fleet to 86 dB.

Case 5 - New production at 83 dB through 1978, retrofit of existing fleet to 83 dB.

Case 6 - 1974 and 1975 production at 83 dB followed by production at 80 dB through 1978. Retrofit existing fleet to 83 dB.

Case 7 - 1974 and 1975 production at 83 dB followed by production at 80 dB through 1978. Retrofit existing fleet and 1974 and 1975 models to 80 dB.

The analysis of resultant fleet noise levels for these cases is given in Table 6.2-1 based upon the assumed national fleet distribution in terms of SAE J366b noise levels.

Table 6.2-1

Analysis of Heavy Truck Non-Tire Noise Reduction Scenarios
Through the Year 1978

Case Number	Percent of Spokane Fleet at Specified Noise Level (Re: SAE J366b) dB						Weighted Energy Mean Level of Fleet dB	ΔL_{eq} from Baseline 1973 dB
	94	92	89	86	83	80		
Baseline 1973	16.4	21.8	42.3	19.5	-	-	90.7	0
1	-	8.3	33.1	58.6	-	-	88.0	2.7
2	-	-	-	100	-	-	86.0	4.7
3	-	-	-	72.7	27.3	-	85.4	5.3
4	-	-	-	56.7	43.3	-	84.9	5.8
5	-	-	-	-	100.0	-	83.0	7.7
6	-	-	-	-	72.7	27.3	82.4	8.3
7	-	-	-	-	-	100.0	80.0	10.7

It should be observed that although some limited cost data do exist for the production and retrofit of heavy trucks to yield resultant levels of 75 dB (SAE J366b),[A5] this level of reduction was not considered technically feasible by 1978 nor cost-effective to incorporate into the analysis.

6.3 AUTOMOBILE SOURCES

Effective countermeasures should be oriented toward treatment of the noisiest subsources in turn until the desired or most cost-effective overall noise levels are achieved for particular modes of operation. As has been pointed out in the foregoing discussions, different sources typically dominate the noise output at different speeds and vehicle configurations.

Appendix E examines the correlation of noise reduction levels as measured by the SAE J986a maximum noise test procedure with observed highway noise levels. There, it is concluded that any reduction in noise level demonstrated by SAE J986a will be reflected directly in observed noise emission only during the acceleration mode, except where tire noise constitutes the lower limit for the speed under consideration. Noise reduction in cruise and deceleration modes is affected to a much lesser degree. The noise levels in each driving mode are then assessed. In cruise mode Eq. (4-1) is applicable. For the deceleration mode, it is assumed that the mean deceleration level varies in accord with the mean level generated during cruise mode at the speed from which deceleration occurs. In determining overall community exposure, it is assumed that noise from idling may be neglected. Appendix E ends with a table (here reproduced as Table 6.3-1) displaying 1973 base-line mean noise levels from automobiles. The subsequent analysis is oriented toward these levels.

6.3.1 Exhaust Noise

Present technology suggests the following modifications to reduce noise from existing automobile exhaust systems: improve muffler design (i.e., larger volume, higher insertion loss), switch from single to dual muffling systems or increase the

Table 6.3-1

Passenger Car - Community Noise Summary
Typical A-Weighted Noise Levels Produced by Mode of Operation

Urban Cycle

GM Cycle G4			SAE Cycle S15		
Mode	% Time in Mode	Energy Mean Level, dB	Mode	% Time in Mode	Energy Mean Level, dB
Idle	14.4	53.5	Idle	13.0	53.5
Acceleration	16.6	70.8	Acceleration	9.5	70.8
Deceleration	16.0	62.4	Deceleration	18.5	62.0
Cruise	53.1	67.3	Cruise	59.0	60.2
Composite Energy Mean Level = 67.1			Composite Energy Mean Level = 63.2		

Suburban Cycle

GM Cycle			SAE Cycle		
Mode	% Time in Mode	Energy Mean Level, dB	Mode	% Time in Mode	Energy Mean Level, dB
Idle	1.1	53.5	Idle	3.1	53.5
Acceleration	4.7	73.8	Acceleration	9.7	73.8
Deceleration	5.8	69.1	Deceleration	11.4	71.7
Cruise	88.4	72.5	Cruise	75.8	70.1
Composite Energy Mean Level = 72.4			Composite Energy Mean Level = 70.7		

exhaust pipe diameter. These modifications successively applied to present vehicles could achieve maximum noise levels (re SAE J986a) of 80 dB. Further reduction (to say, 75 dB) may require additional acoustic shielding around the muffler and pipes to minimize case radiation. Manufacturing cost data for these modifications is meager; however, manufacturers have reported that exhaust pipe diameter increases constitute cost increases of the order of $1 per vehicle. Muffler system improvements may range from $2 to $12 per vehicle, while the cost of adding a dual exhaust system to domestic vehicles may run approximately $25 to $30 per vehicle.

6.3.2 Intake Noise

Industry has demonstrated that this factor may be successfully minimized by the use of larger air cleaners of improved design. Such devices would then be compatible with overall vehicle noise levels of the order of 75 dB. Manufacturers' cost information on this topic is minimal, with one estimate by an imported car manufacturer (subcompact) being given as $.30 per vehicle which represents the incremental manufacturing cost for enlarging the air cleaner.

6.3.3 Fan Noise

Fan noise may be minimized by improved design flex-bladed fans or incorporation of heat sensing demand-type fan clutch systems. It is anticipated that such "quiet fan" systems will be required on lower noise level vehicles of the future. (It should be observed that the large radiator, larger, slower turning fan alternatives used on heavy trucks do not present a rational countermeasure for automobiles.)

The range of estimated costs to the consumer to achieve various levels of reduced maximum noise emission (as determined under full throttle test conditions - SAE J986a) is illustrated in Figure 6.3-1. (It should be noted that, throughout this study, detailed design concepts for noise abatement of highway vehicles have not been defined specifically. Rather, only estimated cost figures versus noise reduction data for the major vehicle noise sources is utilized.)

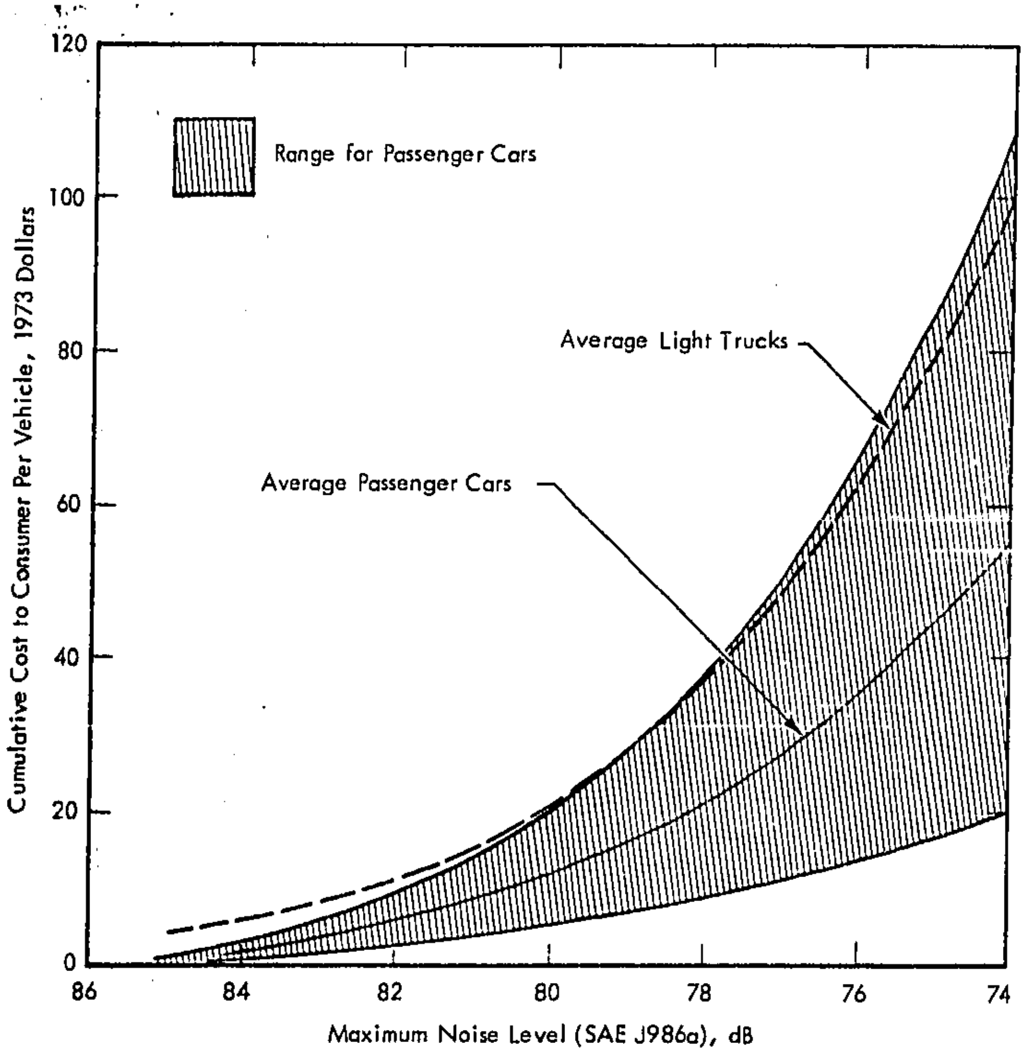

Figure 6.3-1. Costs of Quieting New Automobiles (from References F1, F6, G3, W6)

6.3.4 Automobile Tire Noise

For current passenger automobiles operating at freeway speeds, the tire noise component may be of equal or greater significance than the engine/exhaust. Current tire technology does not offer a feasible means for reduction of high-speed automobile tire noise (at least for automobiles equipped with conventional tires). Thus, for purposes of this analysis through the year 1978, countermeasures for automobile tire noise reduction are not contemplated.

6.3.5 Scenarios of Automobile Noise Reduction

To determine feasible overall noise level reductions for automobiles under urban (low-speed city streets, arterials) and suburban (high-speed highways, freeways) operating conditions, it is necessary to relate specific reductions of SAE J986a levels to reduction of noise emitted in the acceleration, cruise, and deceleration modes.

Acceleration Noise

It is assumed that any reductions in noise level demonstrated by SAE J986a will be directly reflected in observed noise emission during the acceleration mode (except where tire noise constitutes the lower limit for that speed).

For the high-speed case (suburban cycle), the acceleration noise level that can be obtained cannot be lower than the noise level at cruise conditions. The "average speed from which acceleration occurs" is 40.5 mph (Appendix E.2); the corresponding cruise noise level is 68.5 dB (Eq. (4-1)). The acceleration noise level for high-speed conditions is 73.8 dB (from Table E.2-2). It is therefore assumed that the maximum possible reduction of the high-speed acceleration noise level is 73.8 - 68.5 = 5.3 dB.

The corresponding numbers for the low-speed case (urban cycle) are: "average speed from which acceleration occurs: 22.5 mph; corresponding cruise noise level: 61 dB; acceleration noise level (Table E.2-2): 70.8 dB; maximum possible reduction: 70.8 - 61 ≃ 10 dB.

Cruise and Deceleration Noise

We next wish to assess the noise reduction potential of the cruise mode, given the general observation from Figure E.2-2, that the difference between cruise and coast (engine-off) noise levels over a broad range of vehicle speeds is on the order of 3 dB. Thus, we may assume that cruise mode noise levels could conceivably be reduced by this amount if the engine/exhaust contribution were totally eliminated. We assume that the tire component noise levels versus speed are fixed (through the 1978 time period) as the current state-of-the-art of automotive tire/tire tread design does not present a feasible way for its reduction. (Note - it is also possible to reduce deceleration levels by a maximum of 3 dB given the total elimination of the engine/exhaust component.)

The estimated maximum possible reductions in low-speed automobile noise levels, based on the preceding concepts, are given in Table 6.3-2. Thus, the maximum possible low speed energy-mean noise reduction = 67.1 - 62.6 = 4.5 dB. However, we must consider that, realistically, the 10 dB reduction in acceleration levels will not also reflect a 10 dB reduction in the engine component under cruise conditions which is necessary if the full 3 dB reduction in cruise levels (down to just tire noise controlled) is to result. If we assume that the engine component will be reduced by one-half the acceleration component (i.e., 5 dB maximum), then this will reflect a 2 dB reduction in overall cruise and deceleration levels. The effect of this more realistic interpretation of possible noise reduction by mode is oresented in Table 6.3-3. Thus, we may conclude that a more feasible maximum low-speed noise reduction potential of 3.5 dB (67.1 - 63.4) exists given a 10 dB reduction in maximum noise emission levels as specified by SAE J986a.

Next, we need to assess the maximum feasible noise reduction potential under high-speed (suburban) operating conditions. We have stated that the maximum possible reduction under the cruise and deceleration modes is 3 dB, down to the tire-controlled lower limit. However, considering realistically that even a 10 dB reduction in the acceleration noise levels would result in a maximum reduction of the engine/exhaust component under cruise conditions of 5 dB, this yields a net feasible reduction of cruise levels again on the order of 2 dB (engine/exhaust and tire noise). Thus, we may compute the net overall attainable mean noise level reduction as summarized in Table 6.3-4.

Thus, we may conclude that for the same treatment to the automobile population which yields a 3.5 dB reduction in overall low speed mean noise levels (through

Table 6.3-2

Summary of Maximum Obtainable Low Speed Automobile Noise Reduction By Operational Mode for the 1978 Time Period

Mode	Percent Time in Mode (GM Urban Cycle)	Mean Level, dB (Baseline-1973)	Maximum Possible Reduction, dB	Resultant Mean Levels, dB
Idle	14.4	53.5	0	53.5
Acceleration	16.6	70.8	10	60.8
Deceleration	16.0	62.4	3	59.4
Cruise	53.1	67.3	3	64.3
Overall Energy-Mean Level		67.1	4.5	62.6

Table 6.3-3

Summary of Feasible Low Speed Automobile Noise Reduction By Operational Mode for the 1978 Time Period

Mode	Percent Time in Mode (GM Urban Cycle)	Mean Level, dB (Baseline-1973)	Feasible Noise Reduction, dB	Resultant Mean Levels, dB
Idle	14.4	53.5	0	53.5
Acceleration	16.6	70.8	10	60.8
Deceleration	16.0	62.4	2	60.4
Cruise	53.1	67.3	2	65.3
Overall Energy-Mean Level		67.1	≃3.5	63.4

Table 6.3-4

Determination of Maximum Feasible High-Speed Automobile Noise Reduction for the 1978 Time Period

Mode	Percent Time in Mode (GM Suburban Cycle)	Mean Level, dB (Baseline-1973)	Feasible Noise Reduction, dB	Resultant Mean Levels, dB
Idle	1.1	53.5	0	53.5
Acceleration	4.7	73.8	5.3*	68.5
Deceleration	5.8	69.1	2.0	67.1
Cruise	88.4	72.5	2.0	70.5
Overall Energy-Mean Level		72.4	≃ 2.0	70.2

*Cruise level controlled maximum for average speed of 40.5 mph from which acceleration occurs.

a 10 dB reduction in SAE J986a test levels), that a 2 dB reduction (≃ 72.4 - 70.2) will automatically result in the mean high-speed noise emission.

The levels of high- and low-speed overall noise reduction have been correlated in Figure 6.3-2 to SAE J986a test performance levels versus consumer cost per vehicle to achieve these levels.

To arrive at these levels of noise reduction of the automobile population in 1978, it is necessary to define a series of new production and existing fleet noise retrofit scenarios. The four scenarios assumed for automobiles are illustrated in Figure 6.3-3. It is assumed that new production or retrofit down to SAE J986a performance levels of 74 dB (approximately a 10 dB reduction over current production) is the maximum reduction technically feasible by the 1978 time period. This level of noise emission also constitutes the upper limit for which reliable cost data have been obtained from the vehicle manufacturers.

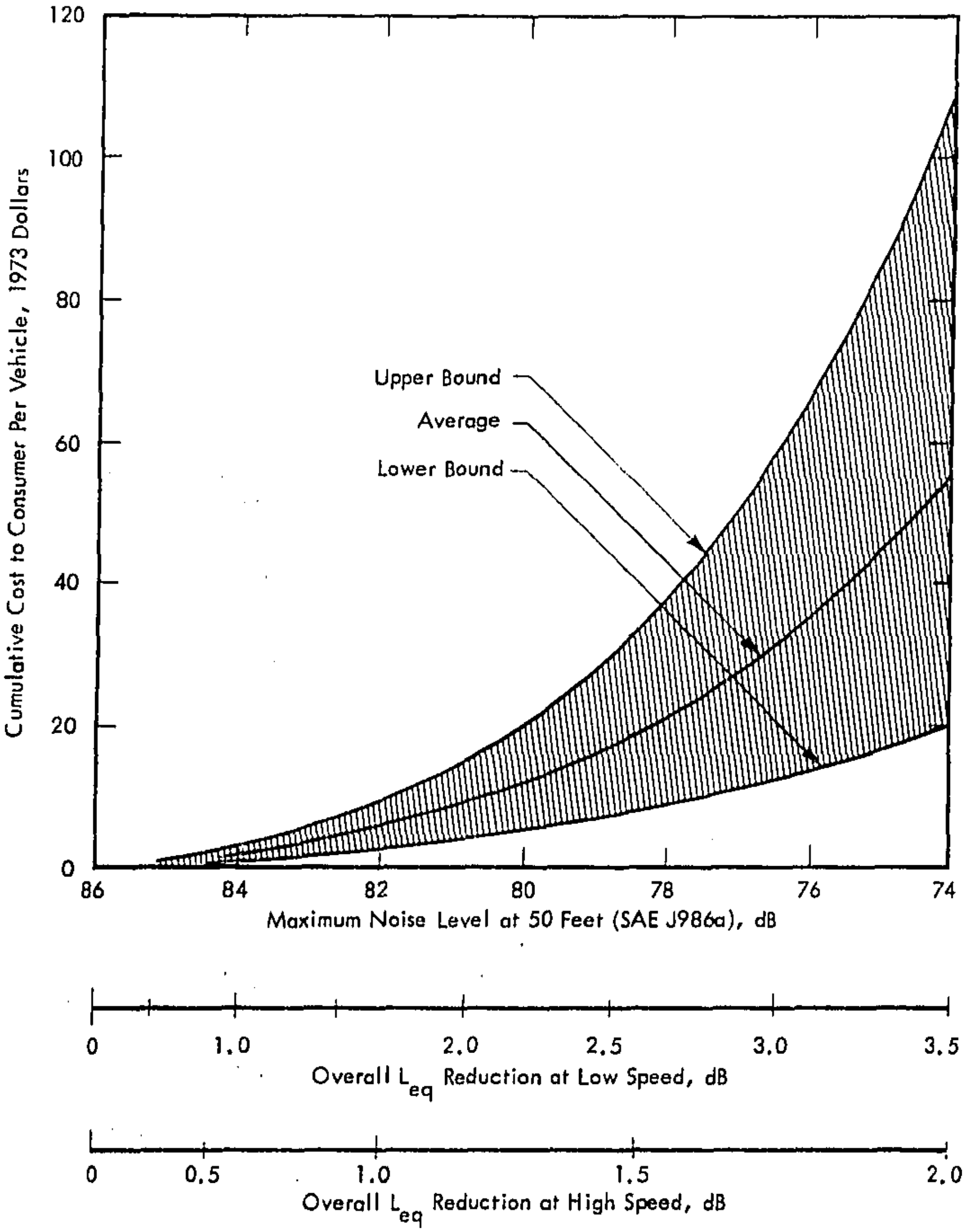

Figure 6.3-2. Automobile Noise Reduction Cost Function (See also Figure 7.4-1)

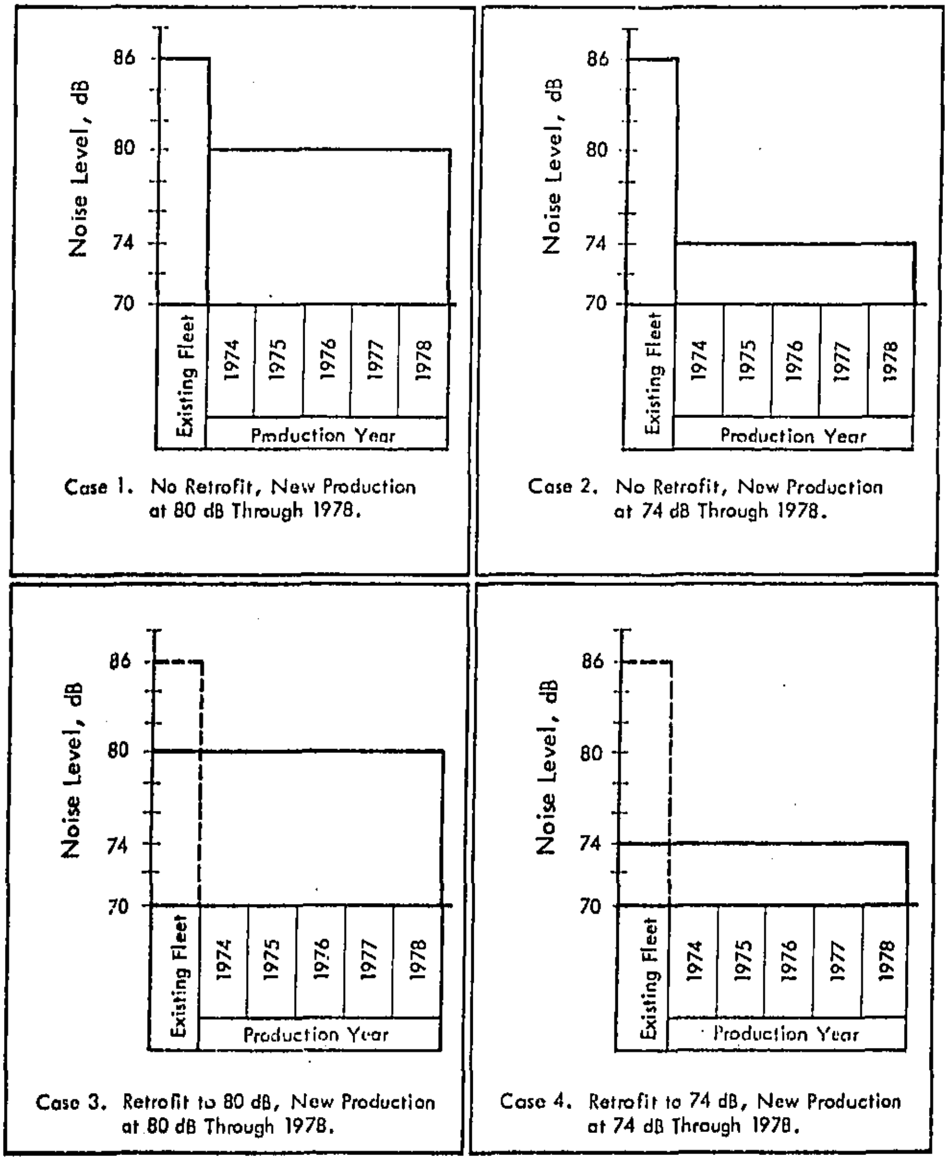

Figure 6.3-3. Definition of Automobile Noise Reduction Scenarios. Vertical Scales: Noise Level in dB According to SAE J986a.

The analysis of the overall automobile fleet mean noise level reductions under urban and suburban driving conditions, based upon the fleet constitution as developed in Section 7.4, and the high- and low-speed noise reductions developed earlier in this section, is presented in Table 6.3-5. These results are then used to construct the L_{eq} - reduction scales in Figure 6.3-2. The upper end of these scales is given by the available cost data. Some subjective judgment was exercised in selecting the lower end at 86 dB. It is also assumed that the scale can be taken as linear. The analysis of present value costs to achieve these scenarios and the development of the noise reduction-cost function are presented in Section 7.4.

6.4 Commercial Bus Sources

To determine the feasible range of noise reduction potential for commercial buses, we must first make some basic assumptions as to their mode of operation and, hence, the correlation of reductions as indicated by the SAE J366b test procedure to the overall fleet mean noise levels, weighted for mode of operation. To begin with, it is assumed that only within the Central Business District (CBD) are bus operations sufficiently concentrated to contribute significantly to the overall noise exposure. Hence, school bus operations and other operations outside of the CBD will not be considered. Thus, given operations only within the CBD, we may describe typical operations as stop-and-go in moderate to heavy traffic with regular passenger pickup stops every block or so. Thus, it would appear that most of the driving time is spent either accelerating or decelerating up to or from maximum speeds on the order of 20 to 25 mph with very little time spent in the cruise mode for these operations. Because diesel buses (with which we are primarily concerned) share many common power train elements and performance features with heavy trucks, we may likewise assume (as in Section 6.2) that any noise reduction indicated by SAE J366b performance levels will be reflected on a one-to-one basis when the bus is operated in the acceleration mode. As a final simplifying assumption, we shall define the typical driving cycle of buses in the CBD as 50 percent acceleration to 20 to 25 mph and 50 percent deceleration

Table 6.3-5

Summary of 1978 Automobile Fleet Noise Reductions for Various Scenarios of Existing Fleet Retrofit and New Production at Reduced Noise Levels (Re: Figure 6.3-3)

Automobile Noise Reduction Scenario	Low Speed Noise Reduction		High Speed Noise Reduction	
	Percent of Fleet	Reduction (ΔL_{eq})	Percent of Fleet	Reduction (ΔL_{eq})
Case 1. No retrofit of existing fleet.	41.5	0	41.5	0
New production at 80 dB (SAE J986a) through 1978.	58.5	-2.2	58.5	-1.3
Overall Reduction	100	-1.5	100	-0.7
Case 2. No retrofit of existing fleet.	41.5	0	41.5	0
New production at 74 dB (SAE J986a) through 1978.	58.5	-3.5	58.5	-2.0
Overall Reduction	100	-1.7	100	-1.1
Case 3. Retrofit existing fleet to 80 dB (SAE J986a).	41.5	-2.2	41.5	-1.3
New production at 80 dB (SAE J986a) through 1978.	58.5	-2.2	58.5	-1.3
Overall Reduction	100	-2.2	100	-1.3
Case 4. Retrofit existing fleet to 74 dB (SAE J986a).	41.5	-3.5	41.5	-2.0
New production at 74 dB through 1978.	58.5	-3.5	58.5	-2.0
Overall Reduction	100	-3.5	100	-2.0

from this speed band. Hence, we may conclude that one-half of any noise reduction indicated by SAE test performance will be reflected in the overall mean noise emission levels of the Spokane commercial bus fleet (CBD operations only). Note that since deceleration noise levels are assumed equal to those of the cruise speed from which deceleration was initiated, they will not be affected by these noise reductions.

The analysis of costs to achieve reductions in terms of SAE test performance down to levels of 70 dB is presented in Section 7.6.

6.5 RAILROAD SOURCES

6.5.1 Introduction

The noise associated with railroad operations is produced by two major components: the diesel-electric locomotives, and the passenger or freight cars. The diesel-electric locomotive is, by far, the most common propulsion system for trains (approximately 99 percent).

The standard locomotive configuration consists of a large 16 to 20 cylinder diesel engine (producing up to 3600 horsepower) that drives an electrical generator. This generator, in turn, provides power to traction motors on each axle of the locomotive. The cooling fans for the radiator portion of the diesel's water cooling system are roof mounted, as are the fans which cool the large resistor banks which are elements of the dynamic braking system. These diesel locomotives are essentially used for two tasks: the larger line locomotives which pull trains, and smaller switcher locomotives (generally less than 1800 horsepower) which classify freight cars in railroad yards and spot small trains of cars to local industries. Of the 27,000 locomotives in use in 1971, approximately one-half fit into each category.

Line locomotives are operated in primarily two modes: full power setting (No. 8 throttle position), which averages 30 percent of the time and, at idle, 41 percent of their running time. Hence, once clear of the classification yard and congested areas, locomotives are operated at high power settings (and thus, maximum noise level) while on main line track. The noise output of line diesel-electric locomotives does not vary significantly with train speed and averages 92 dB at 100 feet. The spectrum of noise emitted by these locomotives is dominated by low frequency exhaust components which are largely de-emphasized by the A-weighting representation. Under dynamic braking conditions (where the wheel traction motors are switched into a generator mode and the power so created is dissipated through the roof mounted resistor banks which are cooled by large fans), the major locomotive noise source becomes the resistor cooling fans which produce noise of a higher frequency content at approximately 5dB less noise. This dynamic braking mode is experienced on the average of 8 percent of the running time. Under idling conditions, which usually occur in the vicinity of the railroad yard, locomotive noise is dominated by the low frequency exhaust component which typically averages 71 dB at 100 feet. Thus, the locomotive noise-contributing subsources may be summarized as follows:

- Diesel exhaust noise
- Cooling fans
- Turbocharger whine (of secondary importance, but may become primary noise source once above two main sources are quieted)

A major source of train-associated noise is the horn or whistle which is required for safety. In surveys of annoyance caused by railroad operations, this has been one of the major offenders, producing up to 110 dB at 100 feet. It is considered inappropriate to consider this factor in the community noise modeling analysis since the noise is a stringent requirement for safety at all ungated crossings and the costs associated with gating such crossings would immobilize an already economically crippled industry. Thus, noise reduction countermeasures for this factor are presently considered either impractical or undesirable and are hence not treated in this effort.

The noise produced by the railroad cars results from interaction of the wheels and rails. It has been shown to increase at a rate of approximately 6 dB for each doubling of train velocity. The magnitude of the noise produced by this wheel/rail interaction depends heavily on the conditions of the wheels and track, whether or not the track is welded (or, more accurately, "high speed classified") and the type of car suspension. Freight cars produce the highest noise levels due to their high unsprung rolling stock mass. Passenger cars, however, typically exhibit 5 to 10 dB less noise due to their hydraulic suspensions and lighter weights. Freight cars additionally produce more noise due to rattling components and larger vibrating sections. Track irregularities, such as grade crossings, switching frogs, bridge crossings, and tight radius curves further accentuate the wheel/rail noise component and may increase its level by up to 20 dB. It has been estimated that approximately 90 percent of the main line track is located outside of heavily populated areas and that most inter-city lines are in commercial or industrial activity areas. This pattern will necessarily shift to higher population exposure with an increased emphasis on rail passenger movements which, to be of good utility, need to be in the proximity of densely populated regions.

Railroad noise countermeasures and their approximate degree of effectiveness are summarized below under the categories of locomotive and car modifications.

6.5.2 Locomotive Noise Countermeasures

In that the diesel engine exhaust is the major noise component, most industry efforts to date have been oriented toward equipping locomotives with exhaust mufflers and modified cooling fan designs. The resultant reductions which have been shown technically feasible have ranged from 8.5 dB on 1500 hp switcher engines with muffler treatment alone to approximately 5 to 6 dB on 2000 to 3600 hp road engines through combined muffler installations and modified fan treatments.[A2] Minimal cost data has been developed on these modifications indicating an expected range of installation costs of from $5,400 to $10,400 per locomotive.[A2] A second, though economically burdening, concept would be the utilization of electrified motive power in "noise-sensitive" areas. This would necessitate additional switching to conventional road power once critical areas are cleared and impose additional time delays as well as significant capital investments in electric locomotives and elaborate catenary systems.

The most feasible countermeasure for implementation by the 1978 time period would be the retrofit of the existing fleet using the aforementioned muffler/fan conversion to gain approximately a 6 dB reduction. As the locomotive component normally accounts for one-half of the acoustic energy of a train passby, this would result in an overall train passby noise reduction of 3 dB.

6.5.3 Railroad Car Noise Countermeasures

Car noise countermeasures are, of necessity, primarily directed toward reducing the noise of wheel/rail interaction. The major potential avenues for correction of this problem have been largely adapted from the more sophisticated rapid transit systems. Hence, the more stringent requirements of freight haulage in terms of heavier duty equipment and durability may reduce the effectiveness of some of these schemes. The more promising of these measures are outlined below.

1. Upgrade the track to "high speed" classified track. This may result in up to a 5 dB noise reduction over jointed, low-speed track; however, it has been observed that noise levels at a given speed are reasonably independent of the track being welded or jointed as long as it is "high speed" classified.[S11]

2. Redesign switching frogs (currently produce 6 to 10 dB increase in wheel/rail noise).

3. Require concrete or heavy design bridge structures - eliminate light steel trestles in populated areas.

4. Reduce occurrence frequency of "bad" wheels on freight cars (i.e., flat spots or built-up tread).

5. Provide shock insulation between rolling stock and freight car bodies (similar concept as passenger car treatment). This could result in a 5 dB reduction.

6. Incorporate usage of resilient wheel designs (i.e., rubber tired vehicles) or wheels with damping treatments incorporated in their designs. Such designs are used to some degree in the more advanced European rapid transit systems and have had moderate success. Generally, these modifications have reduced wheel/rail

noise over smooth straight track by 2 dB but have greatly improved wheel screech emission on curves to where it is nearly nonexistent.

Published cost data on these car noise reduction countermeasures is very limited and the success of the measures in significantly reducing the wheel/rail component noise levels is uncertain. Thus, for the 1978 time period, only locomotive retrofit countermeasures are incorporated insofar as source reductions are concerned.

6.5.4 Trackside Barriers

Trackside barriers have been utilized in some cases to minimize annoyance from train operations; however, there are two fundamental problems associated with their usage. First, they must be placed far enough from the track to allow normal repair and maintenance operations. To the extent that they impair these operations, they are an excessive economic burden. Secondly, barrier effectiveness is a function of the height that the barrier extends above the source of the noise. Hence, for wheel/rail noise, a relatively low barrier (4 to 6 feet) would be reasonably effective (on the order of 8 to 10 dB reduction). The diesel exhaust exit, however, is typically located atop the locomotive some 15 feet above the ground. This suggests that a barrier must exceed at least 15 feet in height before it begins to effectively shield this component. An upper limit of 15 dB noise reduction through the incorporation of trackside barriers has been assumed. A further analysis of barrier effectiveness for various environmental noise sources is presented in Section 6.9.

6.6 AIRCRAFT SOURCES

6.6.1 Introduction

As a general rule, serious noise impact problems near airports are limited to those airports with jet aircraft operations. For this evaluation of aircraft noise countermeasures, therefore, only the jet airports in Spokane are considered. Takeoffs and landings generate high noise levels on the ground level due to development of takeoff thrust and thrust reversal on landing. These create high noise exposure along the runway sideline. Takeoff and climbout, as well as approach operations extend the impact zone further out away from the airport with highest noise exposure occurring directly under the flight paths and diminishing as the sideline distance is increased. (During cruise conditions, current commercial aircraft generally fly at too high an altitude to generate a significant noise impact on the ground unless local ambients are extremely low.) Further noise exposure in the airport vicinity occurs from aircraft maintenance operations and jet engine ground runup tests (either jet engine test stands or stationary aircraft tests).

Results from two major studies on aircraft/airport noise have provided data on noise reduction countermeasures. The first of these studies, recently carried out by EPA in response to the Noise Control Act of 1972, analyzed technical, economic, legal and sociological facets of aircraft/airport noise abatement, including development of a new methodology (the average day-night sound level - L_{dn}) for describing community noise. Results of this extensive study have been published in a series of EPA reports and summarized in a report to Congress.[U10]

The second study, recently completed by Wyle Research for DOT, involved analysis of the cost-effectiveness of three specific aircraft noise source countermeasures: (1) use of a two-segment approach, (2) retrofit of existing aircraft with quiet nacelles, or (3) retrofit with new turbofan components.[B1] Results of these studies have provided an adequate data base for evaluation of the cost-effectiveness of reducing the aircraft-noise portion of community noise using available technology for aircraft noise reduction.

Source countermeasures for noise abatement of jet aircraft operations may be categorized as either physical modifications to the aircraft or operational modifications to reduce noise exposure. The following sections consider a broad variety of such noise abatement measures. Following these general discussions, the specific countermeasures identified for the Spokane analysis are discussed.

6.6.2 Physical Aircraft Modifications

A. Replace noisier aircraft with quieter wide-body types (747, DC-10, L-1011) which incorporate the new technology high bypass ratio turbofan engines.

B. Retrofit existing turbofan aircraft to meet or exceed the requirements of FAR 36. Present studies have considered two basic approaches to retrofit:

(1) Engine housing modifications in the form of "quiet" nacelle treatments (applied to P&W JT3D and JT8D engines).

(2) Engine modifications in the form of quieter design fans in combination with quiet nacelle treatments.

6.6.3 Operational Modifications

- Operational Restrictions

  A. Eliminate noisier aircraft operations at specific airports (i.e., no-jet rules at General Aviation airports). This is sometimes accomplished via relocation of aircraft types or imposed by route swapping agreements.

  B. Cutback in overall air activity resulting from energy shortages; perhaps maintain controls on aircraft fuel allocations for the purpose of reducing emissions.

  C. Impose operating curfews; restrict hours of operations for certain aircraft types; restrict use of flight tracks.

  D. Restrict usage of certain runways by aircraft type, takeoff weight, or direction of operation.

- Operational Procedural Modifications

  A. Require two-segment approaches over "noise sensitive" areas.

  B. Utilize displaced threshold for approach or takeoff where safety considerations are satisfied.

C. Require noise abatement departures, i.e., power cutback.

D. Alter ground tracks to avoid populated areas (hence, minimizing noise exposure). Examples include shoreline departure from Runway 28 at San Francisco International Airport and over ocean approaches at Los Angeles International Airport (LAX).

E. In some instances, higher minimum altitude restrictions may minimize noise impact.

6.6.4 Implementation of Airport Noise Reduction Countermeasures

Implementation of these countermeasures to reduce the cumulative impact of jet aircraft operations may be effected at a number of levels. First, on the Federal level, the FAA could require that all aircraft meet or exceed FAR 36 by a given date or not fly. On the State level, in California for example, the Department of Aeronautics regulations expressed Title 4, Subchapter 6, "Noise Standards," require that cumulative noise exposure for given airport operations be steadily reduced through the year 1985. By this time, airport operating authorities will be required to operate their airport such that the contour of the criterion value of cumulative noise exposure (i.e., CNEL = 65) does not enclose any residential land.

It is expected that these types of airport noise regulations may be met by the aviation industry by instituting the type of operational countermeasures outline above, by imposing fleet-wide noise limits such as envisioned by FAA and EPA in a Fleet Noise Rule, or by implementing the type of aircraft source noise reduction countermeasure defined earlier.

6.6.5 Ground Runup Testing

We assume that aircraft engine test procedures cannot be modified; however, quieter-engined aircraft should produce less ground runup noise. The most effective means of countering ground testing noise are:

A. Restrict hours of ground testing operations (currently, airport authorities have different policies on this point; many have curfews on runup testing while others provide no time restrictions).

B. Install noise barriers around runup test site.

C. Relocate the test sites out of proximity to residential or otherwise "noise-sensitive" areas or to airports where noise is not a problem.

6.6.6 Sound Travel Path Modifications

The primary means by which aircraft noise impact may be lessened by altering the path the sound travels between source and receiver are outlined below.

A. The source to receiver path distance may be increased by rerouting aircraft operations or flight paths away from heavily populated or "noise-sensitive" areas. This may include a shift of heavier or noisier traffic to other facilities or revised runway utilization procedures.

B. Institute land acquisition or rezoning programs in the vicinity of the airport. This may be accomplished by restriction of land use within noise zones incompatible for normal single family dwelling, residential land use to industrial or sound insulated apartment complexes, thus increasing path distance to residential units - also creating an industrial, commercial or otherwise compatible buffer zone, primarily effective for sideline takeoff or ground runup noise. This would also provide beneficial noise reduction directly under the glide slope landing approach path and beneath takeoff tracks.

C. Erect barriers to reduce effect of sideline noise on takeoff and landing immediately adjacent to airport property; also may be effective in reducing noise impact of ground runup operations.

Receiver countermeasures in the form of improvement of the sound insulation of dwellings along with further discussions regarding sound barriers and receiver relocations are given in Section 6.9.

6.6.7 Specific Aircraft Countermeasures Incorporated in the Spokane Analysis

Based upon the foregoing discussion of aircraft noise reduction countermeasures, the following have been selected for cost-effectiveness analysis at Spokane:

A. Two-segment approach (6°/3° glide slope) into Spokane International Airport.

B. Aircraft rerouting by means of modified ground flight tracks to avoid populated areas.

C. Quiet nacelle retrofit of existing commercial aircraft.

D. Implementation of a night flight curfew at Spokane International Airport.

The net effect of these countermeasures is difficult to quantify in terms of a specified number of decibels of noise reduction in that the amount of reduction obtainable varies with position relative to the flight track and distance from the airport. In Case B, for example, flight path rerouting, for some receiver cell locations, aircraft noise impact may be practically eliminated while other locations beneath the rerouted path may experience increased aircraft noise exposure. Similarly, the aircraft engine retrofit affects different modes of aircraft operation to differing degrees. Hence, the analysis of the effectiveness of the countermeasures in reducing aircraft noise exposure has been accomplished by running the Wyle/DOT aircraft noise exposure computer program[B1] with the revised aircraft source emission and operations data for each case and recomputing the resultant exposure at each receiver location (see Section 4.3). The present value cost analysis in quantative terms is conducted in Section 7.8.

6.7 PATH-RECEIVER COUNTERMEASURES

6.7.1 Residential Dwellings

This section summarizes data based on actual experience in the area of modifying existing dwellings to achieve improved sound insulation. The considerations are based upon studies by Wyle and others of actual dwelling improvement in the vicinity of a major airport.[B10, W9] Thus, these modifications are oriented toward treatment of the total dwelling. For ground transportation noise sources or directional stationary sources, it may be possible to achieve desired interior noise levels through treatment only of facing walls. A summary of typical levels of noise reduction is presented in Table 6.7-I for a variety of building types. The soundproofing treatments and the relative effort involved in these modifications are summarized below under the categories of minor, moderate, and major dwelling modifications:

- Minor Dwelling Modifications

Through attention to details such as minimization of "sound leaks" around doors, windows, and vents and replacement of "acoustically weak" components, sound insulation improvements of the order of 7 dB are obtainable. These improvements consist primarily of adequate weatherstripping around doors, assurance of snug fitting doors and windows, elimination of louvered windows, and treatment of exterior vents (chimneys and kitchen or bathroom fans in particular). In addition, exterior hollow core doors need to be replaced with the solid core variety.

- Moderate Dwelling Modifications

Moderate modifications would include all of those listed under "minor" plus increased attention to the weaker housing components; particularly, windows. The most effective window treatments consist of double glazed or sealed windows. In both cases, this usually necessitates air conditioning the dwelling, if not already done. Additional attention is given to the attic by acoustical treatment of attic vents, increased sound absorption material (and hence better heat insulation) in the attic space, and when required, finishing of the crawl space areas with gypsum board. Such treatments will produce improvements in sound insulation over an unmodified unit on the order of 9 dB.

Table 6.7-1

Summary of Outdoor to Indoor Noise Reduction
Provided by Various Categories of Buildings

<table>
<tr><th>Category of Building</th><th colspan="3">Approximate Outdoor to Indoor
Noise Reduction, dB</th></tr>
<tr><td>Single Family Detached
(Ref. S10, App. N)</td><td colspan="2">Windows Open</td><td>Windows Closed</td></tr>
<tr><td>- Warm Climate</td><td colspan="2">9-13 (11)**</td><td>20-27 (26)**</td></tr>
<tr><td>- Cold Climate</td><td colspan="2">13-21 (18)**</td><td>25-30 (28)**</td></tr>
<tr><td>Multiunit Apartments</td><td colspan="3">20-30*</td></tr>
<tr><td>Commercial Buildings,
Offices</td><td colspan="3">25-35*</td></tr>
<tr><td>High Rise Offices</td><td colspan="3">25-35*</td></tr>
<tr><td rowspan="3">Schools (Reference
W8)</td><td colspan="2">Standard Construction</td><td rowspan="2">Acoustically
Treated</td></tr>
<tr><td>Windows Open</td><td>Windows Closed</td></tr>
<tr><td>15.5**</td><td>24.5**</td><td>40.5**</td></tr>
<tr><td>Hospitals</td><td colspan="3">25-35*</td></tr>
</table>

*Estimates based upon field tests of similar structures.

**Weighted for number of rooms contained in sample.

- <u>Major Dwelling Modifications</u>

Major modifications consist of all items under "minor" and "moderate", plus some structural improvements of weak walls and roofs. These changes would include elimination or suitable modification of exposed beam roof/ceiling designs and a general "beefing up" of exterior walls. Sufficient exterior wall improvement may normally be attained by installation of an extra layer of gypsum board on the interior surfaces over sheets of sound deadening board or by securing it to resilient channels. Where possible, double-entry doors or vestibule entrances could be incorporated. In lieu of these, "acoustic" doors are required. Improvements in sound insulation available from these changes may be of the order of 17 dB.

A summary of improvements obtained and the relative costs in 1973 dollars derived from the referenced Wyle study is presented in Table 6.7-2. Additional detail is provided in Table 6.7-3.

Table 6.7-2

Summary of Dwelling Sound Insulation Measures and Relative Costs

Actual construction costs for the modifications (including labor, materials, and contractor's overhead and profit) were as follows: W9

Degree of Modification/ Level of Noise Reduction	Cost per House*	Cost per Square Foot of Floor Area
Minor: ~ 20 dB	$ 3820	$2.50
Moderate: ~ 30 dB	$ 5,740	$3.75
Major: ~ 40 dB	$14,930	$9.75

For soundproofing programs significantly larger than this pilot program, these costs might be reduced approximately 10 to 20 percent.

*Normalized to the average house size (1530 square feet of floor area), and applicable to houses without beamed ceilings.

Table 6.7-3

Summary of Average Costs for Noise Reduction Treatment of 20 Homes in Los Angeles (from Reference W9)

(a) Average Cost for Soundproofing* Stage 1 Houses			
House Elements	Labor	Material	Total
Windows	$ 244	$ 63	$ 307
Doors	190	212	402
Ventilation	776	526	1,302
Miscellaneous	1,226	821	2,047
Total	$2,436	$1,622	$ 4,058
Total Adjusted to Average Floor Area of 1530 Square Feet			$ 3,820

(b) Average Cost for Soundproofing* Stage 2 Houses			
House Elements	Labor	Material	Total
Windows	$1,041	$1,473	$ 2,514
Doors	278	340	619
Beamed Ceiling	484	399	883
Ventilation	1,052	1,190	2,242
Miscellaneous	302	127	430
Total	$3,157	$3,459	$ 6,688
Total Adjusted to Average Floor Area of 1530 Square Feet			$ 5,740

(c) Average Cost for Soundproofing* Stage 3 Houses			
House Elements	Labor	Material	Total
Windows	$1,443	$2,737	$ 4,180
Doors	269	536	804
Ceiling	472	538	1,010
Floors	794	236	1,029
Walls	909	678	1,587
Ventilation	1,250	1,261	2,511
Miscellaneous	863	439	1,302
Total	$6,000	$6,425	$12,423
Total Adjusted to Average Floor Area of 1530 Square Feet			$14,930

*Stage 1 = Minor Modifications (6 Homes)
*Stage 2 = Moderate Modifications (11 Homes)
*Stage 3 = Major Modifications (3 Homes)

The costs for residential sound insulation are summarized in graphical form in Figure 6.7-1. The cost data presented has been adjusted to represent 1973 dollar expenditures.

6.7.2 Commercial Buildings

Estimates of achievable noise reduction in existing commercial buildings have been developed based upon a 1970 study conducted by Wyle Laboratories on modifications to Southern California schools to achieve improved sound insulation.[W8] The results of this study, adjusted to 1973 dollars, are presented in Figure 6.7-2. In that these constructions are indeed typical of a broad range of commercial and light industrial structures, the data developed is assumed applicable to treatment of all categories of commercial structures for the Spokane analysis.

6.7.3 Barriers

An alternative solution to either source noise reduction or receiver protection (either by relocation or improvement in dwelling sound insulation) consists of the incorporation of acoustic barriers between the noise source and the receiver. While much literature is available on the theoretical effectiveness of noise barriers, the basic consideration remains the effective height of the barrier relative to the line of sight between the source and receiver. In practice, it has been shown that barrier effectiveness generally falls somewhat short of predictions by most models, with a practical maximum attenuation of the order of 15 dB rarely actually occurring. The most effective barrier design, from a cost and performance standpoint, appears to be the combination of a concrete or brick wall built upon an earthen mound. A summary of costs of construction and measured (or expected) effectiveness of a variety of roadside highway barriers is presented in Table 6.7-4.

Some typical barrier noise reductions are given in Table 6.7-5 for receiver distances of 50 and 300 feet which appear to be representative distances for concentration of urban residents in the proximity of roadways and railways (see Appendix C.3).

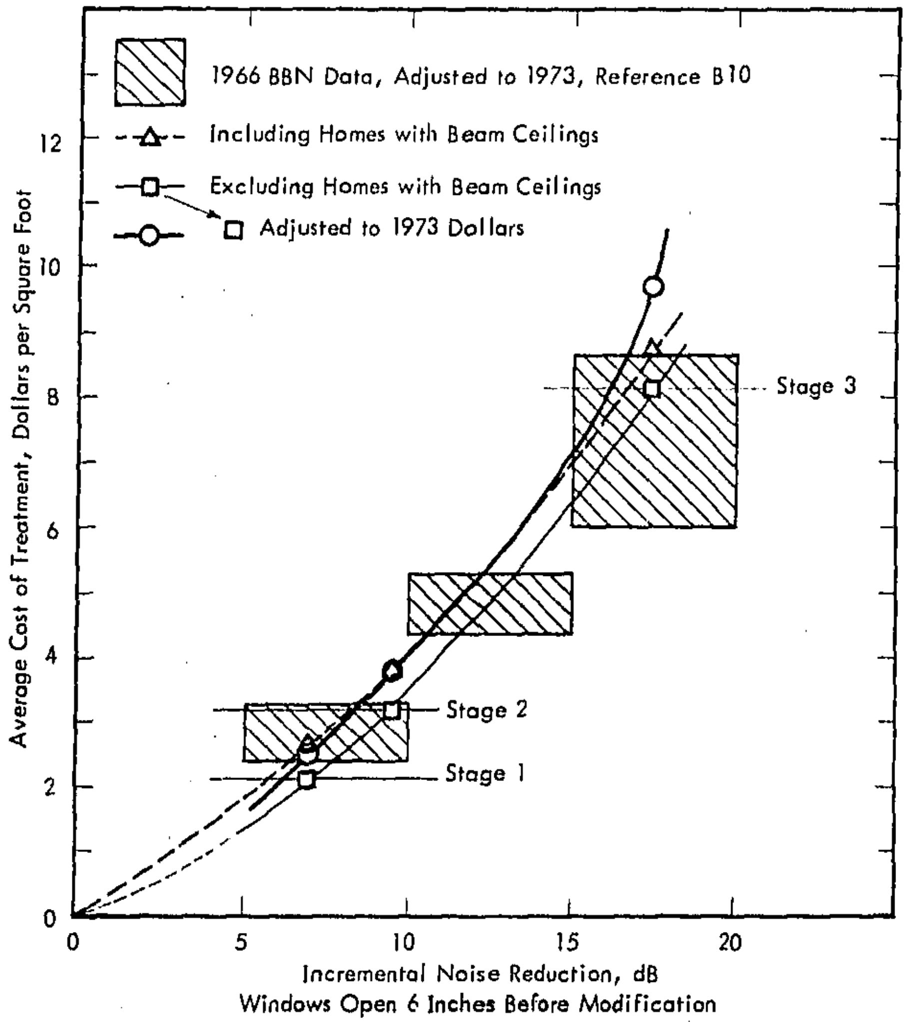

Figure 6.7-1. Average Cost of Residential Soundproofing Treatment for Existing Residences

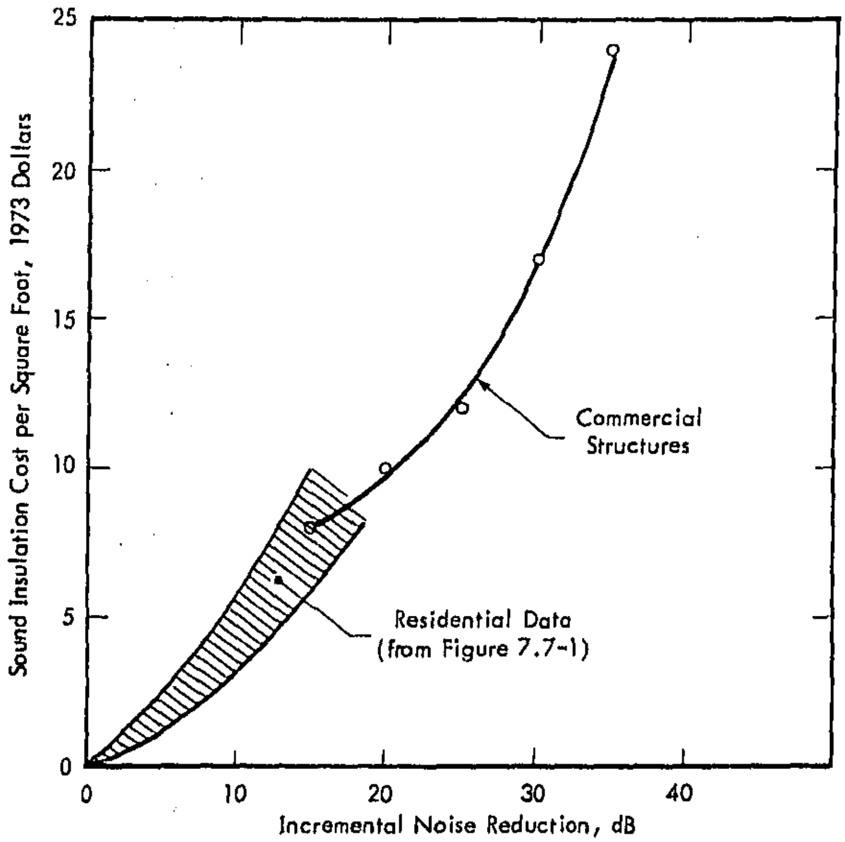

Figure 6.7-2. Costs of Improving Sound Insulation of Commercial Structures (Adapted from Reference N1, Adjusted to 1973 Dollars).

Table 6.7-4

Summary of Highway Barrier Costs and Reported or Expected Effectiveness[U8]

Type	Location	Barrier Height Feet	Cost Per Lineal Foot $	Noise Reduction dB
Earth Berm	I-75, Madison Heights, Mich.	13		8 to 10
Earth Berm	I-94, US 131 Interchange, Kalamazoo, Mich.	10	12.50	7
Earth Berm	I-75, Lake Allatoona, Ga.	15	14.50	
Earth Berm	I-84, West Hartford, Conn.	10 to 15	83.50	10
Earth Berm	Oakdale Road, Georgia	15	27.00	10
Earth Berm	Route 157, Boulder, Colorado	7		6 (Cars) 0 (Trucks)
Earth Berm	Montgomery Co., Maryland	8 to 10		8 to 10
Earth Berm	I-182, Pasco, Washington	10	32.00	10
Earth Berm	S. Madison Beltline, Wis.	10	21.50	12
Earth Berm	North Freeway, Nebraska			9
Earth Berm	St. Paul, Minnesota			10
Earth Berm	Columbia, S. Carolina	11	17.50	7
Timber Wall	Lincoln Park, Mich.	6		0
Timber Wall	I-75, Allen Park, Mich.	14	66.00	10
Timber Wall	127, North Lansing, Mich.	8		0
Timber Wall	I-205, E. Portland, Oregon	10 to 15	46.00	7 to 10
Timber Wall	I-405, Bellevue, Washington	10 to 14	36.50 to 58.00	
Timber Wall	I-90, Tanner, Washington	4 to 12		5 to 10
Timber Wall	North Carolina	10	15.00	0 to 15
Timber Wall	US 59, Houston, Texas	8	7.00	10 at 50 feet
Concrete	I-205, E. Portland, Oregon	10 to 15	73.00	7 to 10
Masonry	Lordsburg, New Mexico	6	25.00	8
Concrete	Sepulveda Blvd., Los Angeles, Ca.	8	65.00	
Concrete	Sepulveda Blvd., Los Angeles, Ca.	9	23.00	
Concrete	Sepulveda Blvd., Los Angeles, Ca.	9	30.00	
Concrete	#92, Hayward, California	6	21.00	
Metal	Phoenix, Arizona	12	328.00	
Concrete	I-94, Minneapolis, Minn.	10 to 23		11 (first row of houses)
Earth Berm + Concrete	Nevada	8		6 to 7 (Trucks)
Earth Berm (+ Wall)	St. Paul, Minnesota			3.8 to 12.4
Earth Berm (+ Wall)	Roseville, Minnesota		68.00	5 to 11
Earth Berm (+ Wall)	Minnesota			2 to 8
Earth Berm + Polyester	Howard Co., Maryland	12	77.00	10
Earth Berm + Steel	Baltimore, Maryland	35		10
Earth Berm + Masonry	Tempe, Arizona	8	8.00	6
Earth Berm + Concrete + Wood	Sacramento, Ca.	5 to 19		10 to 15

Table 6.7-5

Some Barrier Noise Reductions for Typical Cases (in dB)

Barrier 20 Feet from Centerline of Nearest Lane of Roadway						
Barrier Height (feet)	50 Feet			300 Feet		
	Cars	Trucks		Cars	Trucks	
		Low Speed	High Speed		Low Speed	High Speed
8-10	12.5	10	11	12.5	8	10
15*	15	14	15	15	11.5	14

*15 feet is a practical maximum height for barriers. Taller structures become increasingly costly due to the structural requirements to withstand wind and snow loads.

Barrier 50 Feet from Nearest Railway Track, Observer Distance 300 Feet S11		
Barrier Height (feet)	Locomotive	Railway Cars
15	5	15
20	10	15

6.7.4 Sound Receiver Relocation

In many instances, particularly near modern jet airports, the noise levels produced by the activities are so intense as to preclude compatible residential and certain commercial uses of the adjacent land. In some instances, local governments have used their authority for rezoning this severely impacted land, disallowing residential use. In many cases, this has yielded inequitable treatment of residents and has caused considerable controversy in the courts over the concept of inverse condemnation suits filed by the displaced property owners. The concepts utilized in the Spokane analysis avoid this rather complex legal problem. In all cases involving land acquisition, two assumptions are made:

1. The loss of value of the land is limited only to the loss of the value of the property improvements at the time of acquisition.
2. The displaced homeowner or renter receives compensation as determined by the national average paid under such judgments.

The costing for these countermeasures is presented in Section 7.9. Receiver relocation is treated as a high cost extension of the path-receiver noise countermeasure. This provides one continuous cost function for this countermeasure.

CHAPTER 7 .

PRESENT VALUE ANALYSIS OF NOISE REDUCTION COSTS

7.1 INTRODUCTION

The purpose of this chapter is to establish the functional relationship between the amount of noise reduction due to each countermeasure and the cost associated with effecting this noise reduction. Due to the large number of variables influencing costs, only a range of costs can be given so that for each countermeasure, three noise reduction cost functions are identified: low, average, and high costs. The estimated costs are based on the last available information as of September 1974.

In order to put the costs of all countermeasures on an equal footing for use in our cost-effectiveness evaluation, we have used the following method: (This is to prevent comparing the retrofit of a jet engine, which solves the noise problem from that source for 5 years, with the insulation of a house, which solves the noise problem at this receiver for 30 years.) Let us call the cost we assign to each countermeasure its assignable cost. In each case, since costs accrue in different years, we shall calculate the present value of assignable cost to achieve specified levels of source noise reduction or receiver protection and, hence, generate a series of noise reduction cost functions.

We shall speak of first cost, operating cost, and cycle cost. Some definitions are in order.

First Cost (FC) consists of the investment costs necessary to effect a countermeasure, e.g., to retrofit an aircraft engine or to modify a truck already in service. This includes the time the vehicle must be out of service (as a cost to the operator) as well as any hardware and installation labor costs involved.

Operating Cost (OC) includes increments in the cost to operate the vehicle or other capital expenditures due to the noise reduction measure or measures. It may be the increased operating cost of trucks due to greater weight, or increased backpressure, or the cost of air-conditioning in a home without, before it was insulated and had its windows sealed for noise attenuation.

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*All relative and absolute sound levels in dB are A-weighted levels unless otherwise specified.

Also included in operating costs are indirect operating costs such as the cost of reduced payload on a cargo aircraft which is weight-limited.

Cycle Costs (CC) are the increased costs in subsequent replacement cycles of the treated item due to noise reduction measures. In single-firm replacement economic models, firms choose an optimal economic life to minimize the present value of first-cycle and subsequent-cycle costs. This calculation takes into account maintenance costs which tend to rise as a vehicle is kept in service a longer period of time. Then the equipment is sold as 'used' and is filtered down to another user. In this study, we are interested in social costs rather than the costs to a single firm. Therefore, we carry the vehicle, e.g., a truck, through its full service life, 16 years. The cost of subsequent cycles may be, for example, the cost of insulation in a new house when the insulated one is retired, a new barrier, or a new aircraft engine. Future generation aircraft engines are likely to be quieter and more efficient for there is a great deal of technical change in that industry; hence, future cycle costs attributable to noise reduction may be negligible in this specific instance.

In each case, present value analysis is utilized. The present value (PV) of first cost (FC) is usually straightforward. It is just the FC itself if it is all incurred in the initial year.

The present value PV of operating costs is:

$$PV(OC) = \sum_{t=1}^{n} OC_t/(1+r)^t \qquad (7-1)$$

where

OC_t = the incremental operating cost incurred in year t,

n = the remaining service life of the vehicle already in service, e.g., 16 years for a truck, 5 years for a jet engine, and 30 years for a house,

r = the discount rate in percent per year which has been set at 10 percent for this study.

The present value of subsequent cycle cost (CC) is:

$$PV(CC) = \frac{1}{kr} \ (CC) \qquad (7\text{-}2)$$

where k is the service or cycle life in years.

A perpetuity would be capitalized by the factor $\frac{1}{r}$. This is a perpetuity which accrues only in select years, every time a replacement is made. So, if k is the service life of subsequent replacements, we replace one every k years so that this perpetuity accrues (1/k)th of the years. Cycle costs or the costs of subsequent cycles include operating costs during the cycle. If we are investigating the costs of noise reduction measures, it is the increase in cycle costs in which we are interested. This is composed of increased acquisition costs and increased operating costs.

In the cases in which we analyze a continually changing fleet of noise sources, e.g., heavy trucks, automobiles, or buses, etc., it is necessary to consider two aspects of the analysis separately: the treatment of new production units emitting reduced noise levels; and the systematic retrofit of the existing fleet (as required) down to lower levels of noise emission over a defined compliance period (selected as 5 years for our analysis).

7.2 Present Value Analysis of New Production Units

Considering first new production units, we also need to account for the rate of annual growth of the fleet. A relatively straightforward technique has been developed which allows this analysis to be conducted for sources whose volume of operations is increasing at an annual growth rate in the range of 0 to 7 percent. The key to the method is the determination of a "discounted number of future units" where a unit may typically represent a truck, car, or bus, etc.

Two types of costs must be considered: the increase in new product cost due to noise reduction to a specified level; and the increased annual operating costs resulting from the unit being quieted to this level.

The total present value of increased acquisition costs is calculated from:

$$\begin{pmatrix}\text{PV of Increased}\\ \text{Acquisition Costs}\end{pmatrix} = \begin{pmatrix}\text{Increased Acquisition}\\ \text{Cost Per Unit}\end{pmatrix} \underbrace{\begin{pmatrix}\text{No. of New 1973}\\ \text{Units Assigned to}\\ \text{Spokane}\end{pmatrix}\begin{pmatrix}\text{10\% Discounted}\\ \text{Growth Factor}\end{pmatrix}}_{\text{Discounted Number of Future Units}} \quad (7\text{-}3)$$

The discounted growth factor is determined from Figure 7.2-1. Enter the vertical axis at the annual growth rate of the particular noise source and read the factor on the horizontal axis. (One may observe that for the 0 percent growth case, the discount factor equals 10, which corresponds to the Uniform Series Present Worth Computation as $n \rightarrow \infty$ at 10 percent.)

To determine the total Present Value of Increased Operating Costs, we first compute the PV of increased operating costs for a new unit over its life (N years):

$$\begin{pmatrix}\text{PV Increased}\\ \text{Operating}\\ \text{Costs/Unit}\end{pmatrix} = \begin{pmatrix}\text{Increased Operating}\\ \text{Costs Per Year}\end{pmatrix}\begin{pmatrix}\text{PV}\\ i = 10\%\\ N = \text{Life}\end{pmatrix} \quad (7\text{-}4)$$

For example, if we assume heavy trucks producing maximum SAE J366b noise levels of 80 dB cost $75 per year more to operate than 86 dB trucks, and have an average life of 16 years, then

$$\begin{pmatrix}\text{PV}\\ \text{80 dB Trucks}\end{pmatrix} = \$75/\text{Year}\begin{pmatrix}\text{PV}\\ i = 10\%\\ N = 16 \text{ Years}\end{pmatrix} = 75 \times \underbrace{1.1\,\frac{1-\left(\frac{1}{1.1}\right)^{16}}{1-\frac{1}{1.1}}}_{7.824} = \$586.80 \quad (7\text{-}5)$$

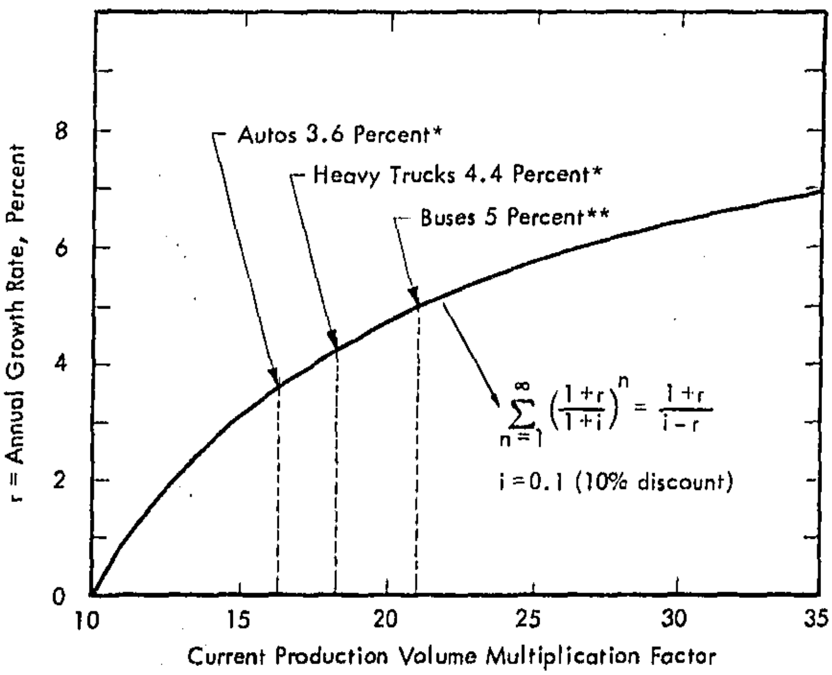

Figure 7.2-1. Determination of Discounted Number of Future Units Incurring Noise Reduction Costs for Given Annual Growth Rates. *From Reference M3, **From Reference S4.

The total present value is then obtained by combining Equations (7-3) and (7-4):

$$\begin{pmatrix}\text{Total Present Value}\\ \text{of Increased Operating}\\ \text{Costs}\end{pmatrix} =$$

$$\underbrace{\begin{pmatrix}\text{Present Value of}\\ \text{Increased Operating}\\ \text{Costs/Unit}\end{pmatrix}}_{\text{From Eq. (7-4)}} \underbrace{\begin{pmatrix}\text{No. of New 1973}\\ \text{Units Assigned}\\ \text{to Spokane}\end{pmatrix} \begin{pmatrix}\text{10\%}\\ \text{Discounted}\\ \text{Growth Factor}\end{pmatrix}}_{\text{Eq. (7-3): Discounted Number of Future Units}} \qquad (7\text{-}6)$$

The logic of the aforementioned method is best illustrated by a detailed specific example.

Given:	Heavy Truck Annual Growth Rate:	4.4 percent
	No. of New 1973 Units Assigned to Spokane:	94.8
	Increased Operating Cost Per Year:	$75.00
	Average Life:	16 Years

Figure 7.2-2 illustrates the detailed formulation of discounted costs for increased operating costs. It also provides the cumulative summation of the discounted number of total new trucks which must be considered. As may be observed, the analysis is carried forward on a year-by-year basis for 50 years. After this time period, both the Cumulative Sum of Discounted Units and the Cumulative Sum of the Discounted Operating Costs are within 93 percent of their limit values.

One may observe that the total discounted number of trucks is approaching the limit of 1735, which is found by multiplying the 1973 production of 94.8 units by the factor of 18.3 (4.4 percent annual growth at 10 percent discount rate) from Figure 7.2-1. Similarly, the limit value for total discounted operating costs may be found from Equation (7-6).

YEAR	NEW UNITS	DISC. FACTOR (@ 10%)	DISC. NO. OF UNITS	CUM SUM OF DISC. UNITS	DISC. PV OF INC. OP. COST	CUM SUM OF DISC. OP. COST
1974	98.88	.9091	89.89	89.9	52746.07	52746.1
1975	103.13	.8264	85.23	175.1	50012.86	102758.9
1976	107.56	.7513	80.81	255.9	47421.28	150180.2
1977	112.19	.6830	76.63	332.6	44964.00	195144.2
1978	117.01	.6209	72.66	405.2	42634.05	237778.3
1979	122.04	.5645	68.89	474.1	40424.83	278203.1
1980	127.29	.5132	65.32	539.4	38330.09	316533.2
1981	132.76	.4665	61.94	601.4	36343.89	352877.1
1982	138.47	.4241	58.73	660.1	34460.62	387337.7
1983	144.43	.3855	55.68	715.8	32674.93	420012.6
1984	150.64	.3505	52.80	768.6	30981.78	450994.4
1985	157.12	.3186	50.06	818.6	29376.36	480370.7
1986	163.87	.2897	47.47	866.1	27654.13	508224.9
1987	170.92	.2633	45.01	911.1	26410.78	534635.6
1988	178.27	.2394	42.68	953.8	25042.22	559677.9
1989	185.93	.2176	40.46	994.2	23744.58	583422.4
1990	193.93	.1978	38.37	1032.6	22514.16	605936.6
1991	202.27	.1799	36.38	1069.0	21347.53	627284.1
1992	210.96	.1635	34.49	1103.5	20241.34	647525.5
1993	220.04	.1486	32.71	1136.2	19192.47	666718.0
1994	229.50	.1351	31.01	1167.2	18197.95	684915.9
1995	239.37	.1228	29.41	1196.6	17254.97	702170.9
1996	249.66	.1117	27.88	1224.5	16360.85	718531.7
1997	260.39	.1015	26.44	1250.9	15513.06	734044.8
1998	271.59	.0923	25.07	1276.0	14709.20	748754.0
1999	283.27	.0839	23.77	1299.8	13947.00	762701.0
2000	295.45	.0763	22.54	1322.3	13224.29	775925.3
2001	308.15	.0693	21.37	1343.7	12539.03	788464.3
2002	321.41	.0630	20.26	1363.9	11889.28	800353.6
2003	335.23	.0573	19.21	1383.1	11273.20	811626.8
2004	349.64	.0521	18.22	1401.4	10689.04	822315.8
2005	364.68	.0474	17.27	1418.6	10135.15	832451.0
2006	380.36	.0431	16.38	1435.0	9609.97	842060.9
2007	396.71	.0391	15.53	1450.5	9112.00	851172.9
2008	413.77	.0356	14.72	1465.3	8639.83	859812.8
2009	431.56	.0323	13.96	1479.2	8192.13	868004.9
2010	450.12	.0294	13.24	1492.5	7767.63	875772.5
2011	469.47	.0267	12.55	1505.0	7365.13	883137.7
2012	489.66	.0243	11.90	1516.9	6983.48	890121.1
2013	510.72	.0221	11.28	1528.2	6621.61	896742.7
2014	532.68	.0201	10.70	1538.9	6278.49	903021.2
2015	555.58	.0183	10.15	1549.0	5953.15	908974.4
2016	579.47	.0166	9.62	1558.7	5644.67	914619.0
2017	604.39	.0151	9.12	1567.8	5352.17	919971.2
2018	630.38	.0137	8.65	1576.4	5074.83	925046.0
2019	657.49	.0125	8.20	1584.6	4811.86	929857.9
2020	685.76	.0113	7.78	1592.4	4562.52	934420.4
2021	715.25	.0103	7.37	1599.8	4326.10	938746.5
2022	746.00	.0094	6.99	1606.8	4101.93	942848.4
2023	778.08	.0085	6.63	1613.4	3889.37	946737.8

Disc. Factor and Disc. No. of Units: Approaches Zero as a Limit

Cum Sum of Disc. Units: Approaches 1735 as a Limit

Cum Sum of Disc. Op. Cost: Approaches 1,018,000 as a Limit

Figure 7.2-2. Present Value of Increased Operating Costs (Computer Printout). This Example Uses a 4.4 Percent Annual Growth Rate and Assumes 94.8 New Units in 1973, a $75 Annual Unit Cost, and a 16 Year Unit Life.

7.3 RETROFIT ANALYSIS OF EXISTING FLEETS

In the analysis of retrofit costs for a particular fleet of noise-producing sources, i.e., cars, trucks, buses, etc., a 5-year compliance period has been specified. This allows treatment of one-fifth of the fleet per year to achieve the desired end results in the 1978 time period. Hence, in that we are effectively deferring retrofit capital expenditures for certain segments of the fleet until later years, it is more convenient to determine a "discounted number of units treated" in a manner similar to the approach taken for new units. We are dealing with a discrete number of units to be treated which may be determined by considering the annual growth and scrappage rates and thus determining which percentage of the 1978 fleet is comprised of post-1973 production and that portion which is pre-1973 and may require noise reduction modifications. It is then assumed that one-fifth of this number will be treated per year. Thus, we may determine the discounted number of units treated by summing the present value discount factor over 5 years as follows:

$$\begin{pmatrix}\text{Discounted}\\ \text{Number of}\\ \text{Units Treated}\end{pmatrix} = \begin{pmatrix}\text{Annual}\\ \text{Number}\\ \text{Treated}\end{pmatrix} \times \left[1 + \sum_{n=1}^{4} \frac{1}{(1+i)^n}\right] = 4.17 \times \begin{pmatrix}\text{Annual}\\ \text{Number}\\ \text{Treated}\end{pmatrix} \qquad (7\text{-}7)$$

where i = 10 percent discount rate.

Thus, we arrive at the present value of retrofit first costs (excluding for the present, discussion of increased operating costs due to retrofit):

$$\text{PV(Retrofit FC)} = \begin{pmatrix}\text{Average FC}\\ \text{Per Unit}\end{pmatrix} \times \begin{pmatrix}\text{Discounted Number of}\\ \text{Units Treated [Eq. (7-7)]}\end{pmatrix} \qquad (7\text{-}8)$$

If it is also necessary to include the consideration of increased operating costs for units treated over their remaining service lives (N), an additional cost must be included. For a single unit, the present value of increased operating costs may be determined from the expression:

$$\begin{pmatrix} \text{PV(OC)} \\ \text{Single Unit} \end{pmatrix} = \left[\sum_{n=1}^{N} \frac{1}{(1+i)^n} \right] \times \text{Annual Increased Operating Costs/Unit} \qquad (7\text{-}9)$$

where $i = 10$ percent.

Thus, the present value of increased operating costs for all units to be retrofitted is determined as follows:

$$\begin{pmatrix} \text{PV Increased Operating Costs} \\ \text{for all Treated Units} \end{pmatrix} = \begin{pmatrix} \text{PV(OC)} \\ \text{Single Unit} \end{pmatrix} \times \begin{pmatrix} \text{Discounted Number of} \\ \text{Units Treated} \end{pmatrix} \qquad (7\text{-}10)$$

Hence, the total assignable retrofit costs are

$$\text{PV(Retrofit Costs)} = \underbrace{\text{PV(Retrofit FC)}}_{\text{Eq. (7-8)}} + \underbrace{\text{PV(Retrofit OC)}}_{\text{Eq. (7-10)}} \qquad (7\text{-}11)$$

The following sections present the derivation of the noise reduction cost functions for those levels of feasible countermeasure application as defined in Chapter 6. The basic first cost and operating cost data developed in Chapter 6 is utilized to yield the final present value cost functions. Costs for countermeasures indigenous to Spokane are treated as local costs; costs for countermeasures which must be implemented at the national level are assigned costs on a pro rata basis for Spokane only.

7.4 AUTOMOBILE NOISE REDUCTION

For the Spokane, Washington, analysis, we have assigned 140,000 automobiles to Spokane for the 1973 time period:

$$\begin{pmatrix} \text{Number of 1973 Units} \\ \text{Assigned to Spokane} \end{pmatrix} = \begin{pmatrix} \text{Number of Total} \\ \text{Washington Registrations} \end{pmatrix} \begin{pmatrix} \frac{\text{Population of Spokane County}}{\text{Total Washington Population}} \end{pmatrix}$$

$$= 1{,}643{,}000^{*} \quad \frac{283{,}077^{**}}{3{,}352{,}892^{**}} = 138{,}700 = 140{,}000 \qquad (7\text{-}12)$$

* Source: Ref. U2

** Source: Ref. U3

Thus, referring to Figure 6.3-1, which summarizes the consumer cost per new vehicle to achieve reduced levels of maximum noise emission (as determined by SAE J986a) and correlates these SAE levels to expected overall reductions under normal low- and high-speed driving conditions (as derived in Chapter 6), we may proceed with the analysis of costs to achieve the four noise reduction scenarios defined earlier in Figure 6.3-3.

7.4.1 Increased Acquisition Cost Analysis for New Production Units

Case 1. No retrofit of existing fleet – new production at 80 dB (SAE J986a) through 1978.

Assumptions:

a. Annual rate of growth of Spokane automobile fleet: +3.6 percent (based upon a compilation of new car registration statistics indicating a 12.6 percent rate, and annual scrappage rate for the U.S. from 1960 to present of 9 percent).[A4] Applies to all cases.

b. Range of new production costs per vehicle: $5 to $20 (re: Figure 6.3-1).

c. Increased operating costs due to noise reduction: none (applies to all cases).

d. Due to the limited availability of cost data, it is assumed that the range of costs for vehicles requiring retrofit is identical to that for new production units — applied to Cases 3 and 4 only. (However, see next section describing a substudy probing this assumption.)

Analysis:

Number of new 1973 units assigned to Spokane = 140,000 x (average new registration rate) = 140,000 x .126 = 17,640

10 percent discounted growth factor (at +3.6 percent annual overall growth rate from Figure 7.2-1: 16.2.

Thus: Discounted number of future units = 16.2 x 17,640 = 285,768.

Increased acquisition cost per unit = $5 to $20.

Thus: Range of present value of increased acquisition costs = ($5 to $20) x (285,768) = $1.43 to $5.72 x 10^6.

Case 2. No retrofit of existing fleet, new production at 74 dB (SAE J986a) through 1978.

Assumptions: As in Case 1 except,

a. Increased acquisition cost per unit = \$20 to \$110.

Analysis: Discounted number of future units: 285,768.

Thus: Range of present value of increased acquisition costs = (\$20 to \$110) x (285,768) = \$5.72 to \$31.4 x 10^6.

Case 3. Retrofit existing fleet to 80 dB (SAE J986a), new production at 80 dB through 1978.

Analysis: New production costs as in Case 1, retrofit analysis presented in Section 7.4.2.

Case 4. Retrofit existing fleet to 74 dB (SAE J986a), new production at 74 dB through 1978.

Analysis: New production costs as in Case 2; retrofit analysis follows.

7.4.2 Automobile Noise Reduction Retrofit Analysis

Table 7.4-1 shows the growth of the Spokane automobile fleet. Of the 167,080 automobiles charged to Spokane in 1978, 94,781 are new production units (since 1973) and 72,299 are pre-1973 — potentially requiring noise reduction retrofit. Hence, to achieve the overall fleet noise reductions as indicated in Cases 3 and 4, we wish to retrofit 14,460 units per year over 5 years.

The evaluation of the discounted number of units requiring retrofit over the 5-year compliance period is presented in Table 7.4-2.

Table 7.4-1

Analysis of Spokane Automobile Fleet Through 1978

Year	Number of Units at Beginning of Year	Number Scrapped (9% Average Rate*)	Number Added (12.6% Average New Regs.*)	Total Fleet at Year End (3.6% Average Growth Rate*)
1973	140,000	12,600	17,640	145,040
1974	145,040	13,054	18,275	150,261
1975	150,261	13,524	18,932	155,670
1976	155,670	14,010	19,614	161,275
1977	161,275	14,515	20,320	167,080
1978	167,080			

*Based upon averaging of new vehicle registration and annual scrappage statistics from 1960 to present — Source: Automotive News Almanac Issue - 1973.

Table 7.4-2

Determination of Discounted Number of Automobiles Retrofitted

Year	Number of Automobiles Retrofitted	PV Discount Factor at 10%	Discounted Number of Units Treated
1973	14,460	1.0	14,460
1974	14,460	0.909	13,144
1975	14,460	0.826	11,944
1976	14,460	0.751	10,859
1977	14,460	0.683	9,876
1978	0		
Totals	72,300	4.17	60,283

Thus, the present value of retrofit costs to achieve a given noise level reduction is equal to the cost to achieve that level for a single automobile multiplied by the "discounted number of units treated" (60,283).

The costs of installing the retrofit hardware could not be determined with any certainty, not only here for automobiles, but for all motor vehicles. One may expect that it will be more expensive to install a retrofit part in the field than on the assembly line. However, this need not always be the case. Since a retrofit period of 5 years is allowed, installing an improved muffler, for example, can be delayed until such time when the original component needs replacement anyway. For the major portion of the study, it has been assumed that the retrofit cost, i.e., for parts and labor, equals the incremental retail costs of manufacturing new units which also consist of hardware and labor costs. In order to demonstrate the sensitivity of the results of this study to the retrofit labor costs as far as motor vehicles are concerned (labor costs are included for locomotive and aircraft retrofit; see later), the following substudy is carried out:

- Cost functions are developed for motor vehicles (automobiles, trucks, buses) for both the basic assumption that the total retrofit costs equal the new unit incremental manufacturing costs, and for the assumption that retrofit labor costs equal double the hardware costs. For the latter case, the costs for retrofitting one unit are then three times those of the former (basic) case.
- Only at the highest level of noise reduction (i.e., for the quietest vehicles) are the costs computed also for the case with tripled hardware costs (see, for example, case below pertaining to automobiles). The corresponding cost function is then obtained by multiplying the basic function by a constant factor.
- Section 8.3.4 describes how the increased cost functions are used in the retrofit labor cost sensitivity substudy. Calculations associated with this substudy are denoted by brackets ([ ]).

Anticipating no increased operating costs, the retrofit costs assignable to Spokane for Cases 3 and 4 may be determined:

Case 3. Retrofit to 80 dB

Estimated cost per vehicle to achieve 80 dB (re: Figure 6.3-1):

$5 to $20/vehicle x 60, 283 (discounted number of vehicles) = $301,000 to $1,206,000.

Case 4. Retrofit to 74 dB

Estimated cost/vehicle to achieve 74 dB (re: Figure 6.3-1):

$20 to $110/vehicle x 60,283 = $1,206,000 to $6,631,000.
[3,618,000] [19,893,000]

Note: No increased costs to operate are assumed for Cases 3 and 4.

Thus, the range of total costs for Cases 3 and 4 equals the new production costs plus retrofit costs.

Case 3:

$1.43 to $5.72 x 10^6 + $0.3 to $1.2 x 10^6 = $1.73 to $6.92 x 10^6

and

Case 4:

$5.72 to $31.4 x 10^6 + $1.2 to $6.63 x 10^6 = $6.92 to $38 x 10^6.
[3.6] [19.9] [9.32] [51.3]

[Multiplier = (9.32 + 51.3)/(6.92 + 38) = 1.35, i.e., a 35 percent increase]

The range of costs for the four cases are plotted versus the computed low- and high-speed noise reductions in Figure 7.4-1. The low-, medium-, and high-range noise reduction functions have been drawn through the optimum of the scenarios analyzed.

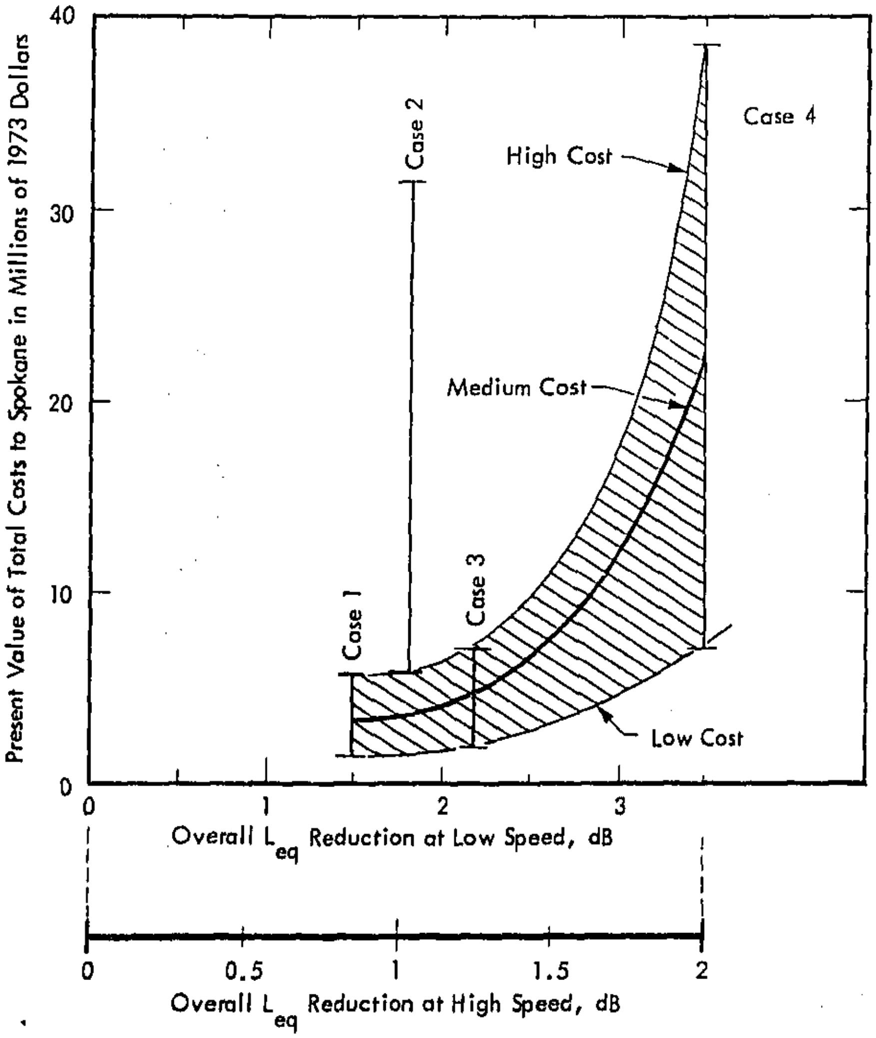

Figure 7.4-1. Noise Reduction Cost Functions for Automobiles [For Case with Tripled Retrofit Hardware Costs: Multiply Functions Shown by 1.35].

7.5 HEAVY TRUCKS

In order to spare the casual reader the task of ploughing through a detailed analysis of the present value of heavy truck noise reduction, the latter analysis has been placed in Appendix G. The results are summarized here. Table 7.5-1 and Figure 7.5-1 pertain to low-speed noise reduction; they are self-explanatory. The case for tripled retrofit hardware costs is again shown in brackets ([ ]). For the high-speed case, Appendix G computes the range of costs associated with equipping trucks with quieter rib-design tires; the result is 1.7 to 2.7 million 1973 dollars for Spokane, Washington.

7.6 CITY BUS NOISE REDUCTION

For the Spokane analysis, only commercial bus activity in the Central Business District has been considered in terms of noise impact from bus operations. School buses and commercial bus activity outside of the CBD is randomly distributed throughout the city and not sufficiently concentrated to contribute significantly to the noise environment. Within the CBD, however, there is a high level of bus activity which does constitute a significant portion of the overall noise levels. The allocation of commercial buses for this analysis was based upon the total number of such buses registered in Washington State factored by the population of Spokane County over the Washington State population as follows:

$$\begin{pmatrix}\text{Number of 1973}\\ \text{Commercial Buses}\\ \text{Assigned to Spokane}\end{pmatrix} = \begin{pmatrix}\text{Number of Registered}\\ \text{Commercial Buses}\\ \text{in Washington}\end{pmatrix} \left(\frac{\text{Population of Spokane County}}{\text{Total Washington Population}}\right)$$

$$= \quad (537^{*})\left(\frac{283,077^{**}}{3,352,892^{**}}\right) = 45 \qquad (7\text{-}13)$$

*Source: Ref. U4
**Source: Ref. U3

Table 7.5-1
Summary of Present Value of Total Costs to Achieve Heavy Truck Noise Reduction Scenario Cases 1 Through 7[1]
[Case of Tripled Retrofit Hardware Costs in Brackets]

Noise Reduction Scenario (Noise Levels re:SAE J366b)	Resultant Low Speed Noise Reduction, dB (re: Section 7.2)	Range of Present Value of Costs to Achieve Noise Reduction Scenario, in Millions of 1973 Dollars[2]				
		Increased New Acquisition	Increased Operation - New Units	Retrofit Existing Fleet	Increased Operation - Retrofitted Units	Total
Case 1. Continue production at 86 dB - no retrofit	2.7	0	0	0	0	0
Case 2. Continue production at 86 dB - retrofit to 86 dB	4.7	0	0	0.04 to 0.20	0	0.04 to 0.20
Case 3. 1974 and 1975 production at 86 dB, 1976 + production at 83 dB - retrofit to 86 dB	5.3	0.47 to 0.94	0	0.04 to 0.20		0.51 to 1.14
Case 4. New production at 83 dB - retrofit to 86 dB	5.8	0.52 to 1.04	0	0.04 to 0.20	0	0.56 to 1.24
Case 5. New production at 83 dB - retrofit to 83 dB	7.7	0.52 to 1.04	0	0.15 to 0.42	0	0.67 to 1.46
Case 6. 1974 and 1975 production at 83 dB, 1976 + production at 80 dB - retrofit to 83 dB	8.3	0.75 to 1.51	0.92	0.15 to 0.42	0	1.82 to 2.85
Case 7. 1974 and 1975 production at 83 dB, 1976 + production at 80 dB - retrofit 1974 & 1975 and existing fleet to 80 dB	10.7	0.75 to 1.51	0.92	0.26 to 0.476 [0.76 to 1.43]	0.27	2.2 to 3.17 [2.7 to 4.13]

(1) Scenarios defined in Figure 7.2-1.
(2) Costs for only the truck population assigned to Spokane, Washington.

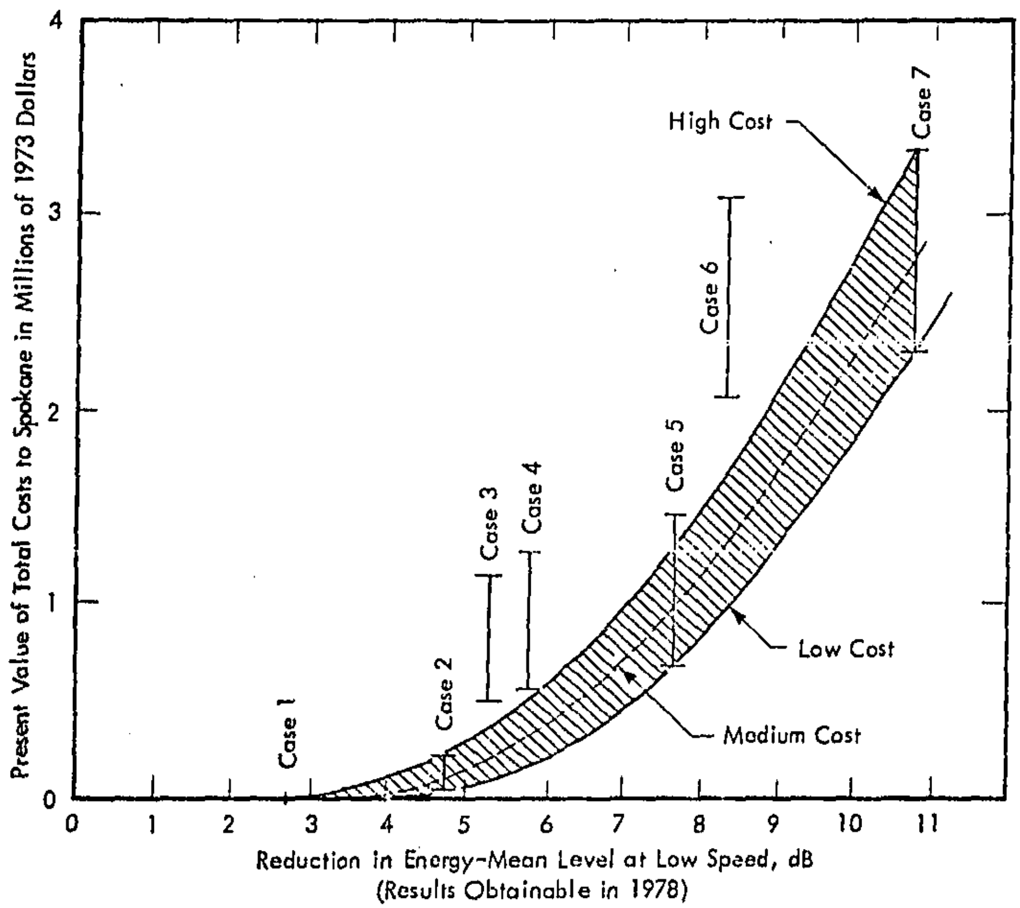

Figure 7.5-1. Present Value of Heavy Truck Noise Reduction Costs [Case of Tripled Retrofit Hardware Costs: Multiply Cost Functions Shown by 1.3]

The basic cost information utilized in this analysis is based upon achievement of specific levels of maximum noise emission as determined by SAE Test Procedure J366b and is presented in Figure 7.6-1. This data represents a compilation from many sources, in some cases referring to new production costs, while in others, based upon costs of presently available stock and modified "Environmental Improvement Kits" offered by General Motors for some of their existing and current production model buses.[W10] Also superimposed on this figure is the assumed correlation between reductions in SAE test performance levels and anticipated mean fleet noise level reductions developed in Section 6.4.

The analysis of present value of total costs to achieve overall levels of fleet noise reduction of from 1.5 to 8 dB through the 1978 time period assumes that for each level of reduction analyzed (1.5, 3, and 8 dB corresponding to SAE test levels of 83, 80, and 70 dB), new production units through the 1978 time period are at these levels and that by 1978, over a 5-year retrofit program, the existing fleet also achieves these levels. Thus, we may proceed with the analysis of the Spokane fleet composition through the 1978 time period assuming a 5 percent annual rate of growth as shown in Table 7.6-1.[S4]

Table 7.6-1

Spokane Commercial Bus Fleet Through 1978

Year	Number of Units at Beginning of Year	Fleet at Year's End Assuming a 5% Annual Growth Rate
1973	45	47.3
1974	47.3	49.6
1975	49.6	52.1
1976	52.1	54.7
1977	54.7	57.4
1978	57.4	

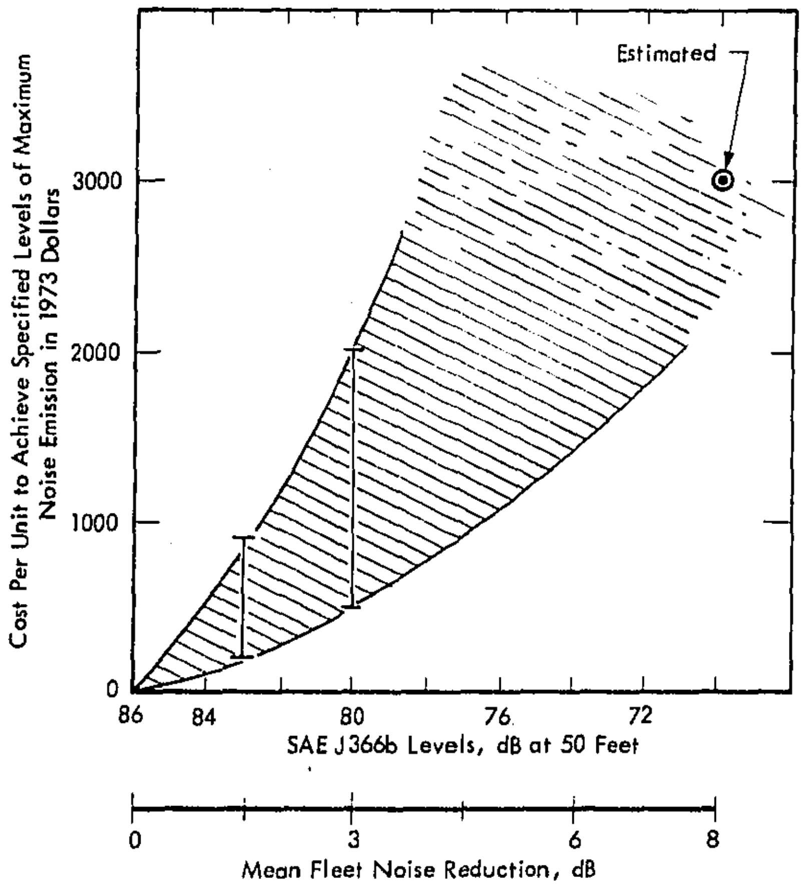

Figure 7.6-1. Unit First Cost Versus Maximum Noise Level (SAE J366b) for Commercial Buses

For purposes of analysis, we have assumed a 10 percent annual new registration rate and a 5 percent annual scrappage rate, leading to an overall annual growth rate of +5 percent. Thus, the 1978 fleet of 57.4 units is assumed to consist of 25 post-1973 new production units and 32.4 pre-1973 units requiring retrofit to the specified SAE test performance levels. The analysis of costs to achieve the specific cases follows:

7.6.1 Increased Acquisition Costs

Case 1: Entire 1978 Fleet Meets 83 dB (SAE J366b) Specifications.

Number of new 1973 production units assigned to Spokane

= (total 1973 fleet) (new registration rate)
= (45) (10%) = 4.5 units

10% discounted growth factor (at +5% overall annual growth rate) from Figure 7.2-1: 21.

Thus, discounted number of future units = (4.5) (21) = 94.5

Range of increased acquisition costs per unit (Figure 7.6-1): $200 to $900 yielding range of present value of increased acquisition costs:

($200 to $900) (94.5) = $18,900 to $85,050

Case 2: Entire 1978 Fleet Meets 80 dB (SAE J366b) Specifications.

Discounted number of units (from Case 1): 94.5

Range of costs of achieve 80 dB (Figure 7.6-1): $500 to $2000

Thus, range of present value of increased acquisition costs:

($500 to $2000) (94.5) = $57,300 to $189,000

No increased operating or maintenance costs are assumed for Cases 1 and 2.

Case 3: Entire 1978 Fleet Meets 70 dB (SAE J366b) Specifications.

Discounted number of units (from Case 1): 94.5

Range of costs to achieve 70 dB (Figure 7.6-1): $3000 (estimate)

Present value of increased acquisition costs: ($3000) (94.5) = $283,500

Increased operating costs: A one percent increase in fuel consumption resulting from increased exhaust system backpressure has been assumed. Based upon 1970 Highway Statistics - Statistical Abstracts of the U.S., the average commercial bus uses 2491 gallons of fuel per year. Therefore, 1% = 24.9 gallons/year at $.50/gallon = $12.50/year. Assuming a useful life of new production units of 16 years (as for heavy trucks), the present value of increased operating costs per unit is:

$$\begin{pmatrix}\text{PV Increased Operating} \\ \text{Cost/Unit}\end{pmatrix} = (\$12.50/\text{year}) \begin{pmatrix}\text{PV} \\ i = 10 \text{ percent} \\ n = 16 \text{ years}\end{pmatrix}$$

$$= (\$12.50)(7.824) = \$97.80/\text{unit} \qquad (7\text{-}14)$$

Hence, the total present value of increased operating costs of new production units = ($97.80/unit)(94.5: Discounted Number of Future Units)
= $9200.00

7.6.2 Commercial Bus Retrofit Analysis

Of the assumed 1978 Spokane commercial bus fleet, we will need to assess retrofit costs for 32.4 units. As in previous analyses, we assume a 5-year compliance period, and hence, must treat ~6.5 buses per year. The evaluation of the discounted number of units requiring retrofit over this period is presented in Table 7.6-2. Thus, for Cases 1 through 3, we may compute the present value of first costs by multiplying the range of costs for a single unit to achieve a specified level by the discounted number of units treated as follows (as in the automobile retrofit analysis, Section 7.4.2, the tripled retrofit hardware costs are shown in brackets ([ ]) for Case 3):

Case 1. Retrofit to 83 dB

Range of costs per unit: $200 to $900 (Figure 7.6-1)

Present value of retrofit costs: ($200 to $900) (27.1) = $5400 to $24,400

Table 7.6-2

Determination of Discounted Number of Commercial Buses Requiring Noise Reduction Retrofit

Year	Number of Buses Retrofitted	PV Discount Factor at 10 Percent	Discounted Number of Units Treated
1973	6.5	1.0	6.5
1974	6.5	.909	5.9
1975	6.5	.826	5.4
1976	6.5	.751	4.9
1977	6.5	.683	4.4
1978	0		
Total	32.5	4.17	27.1

Case 2. Retrofit to 80 dB

Range of costs per unit: $500 to $2000 (Figure 7.6-1)

Present value of retrofit costs: ($500 to $2000)(27.1) = $13,600 to $54,200

No increased operating costs assumed for Cases 1 and 2.

Case 3. Retrofit to 70 dB

Range of costs per unit: $3000 - estimate (Figure 7.6-1)

Present value of retrofit costs: ($3000)(27.1) = $81,300 [162,600]

Assumed increased operating costs: $12.50 per year in increased fuel consumption (re: Case 3 — new production analysis)

Remaining useful life: 8 years

Thus, the present value of increased operating costs per unit is:

$$\begin{pmatrix}\text{PV Increased}\\ \text{Operating}\\ \text{Cost/Unit}\end{pmatrix} = (\$12.50/\text{Year})\begin{pmatrix}\text{PV}\\ i = 10\%\\ N = 8 \text{ Years}\end{pmatrix} = (\$12.50)(5.335) = \$66.70 \qquad (7\text{-}15)$$

Hence, the total present value of increased operating costs for retrofit of existing fleet to 70 dB = ($66.70)(21.7: Discounted Number of Retrofit Units) = $1400.

The cost components for Cases 1 through 3 are summarized in Table 7.6-3 and the resultant fleet noise reduction (re: the analysis conducted in Section 6.4) versus present value of total costs in 1973 dollars for commercial buses is presented in Figure 7.6-2.

Table 7.6-3

Summary of Present Value of Total Costs to Achieve Commercial Bus Noise Reduction Cases 1 Through 3
[Brackets Indicate Tripled Retrofit Hardware Costs]

Definition of Noise Reduction Cases (Noise Levels Re: SAE J 366b)	Resultant Low Speed Noise Reduction (Re: Section 7.4)	Range of Present Value of Costs to Achieve Noise Reduction Cases in Thousands of 1973 Dollars				
		Increased New Acquisition	Increased Operation - New Units	Retrofit Existing Fleet	Increased Operation - Retrofitted Units	Total
Case 1. New Production at 83 dBA. Retrofit to 83 dBA.	1.5	18.9 to 85	0	5.4 to 24.4	0	24.3 to 109.4
Case 2. New Production at 80 dBA. Retrofit to 80 dBA.	3.0	47.3 to 189	0	13.6 to 54.2	0	60.9 to 243.2
Case 3. New Production at 70 dBA. Retrofit to 70 dBA.	8.0	283.5	9.2	81.3 [244]	1.4	375.4 [536]

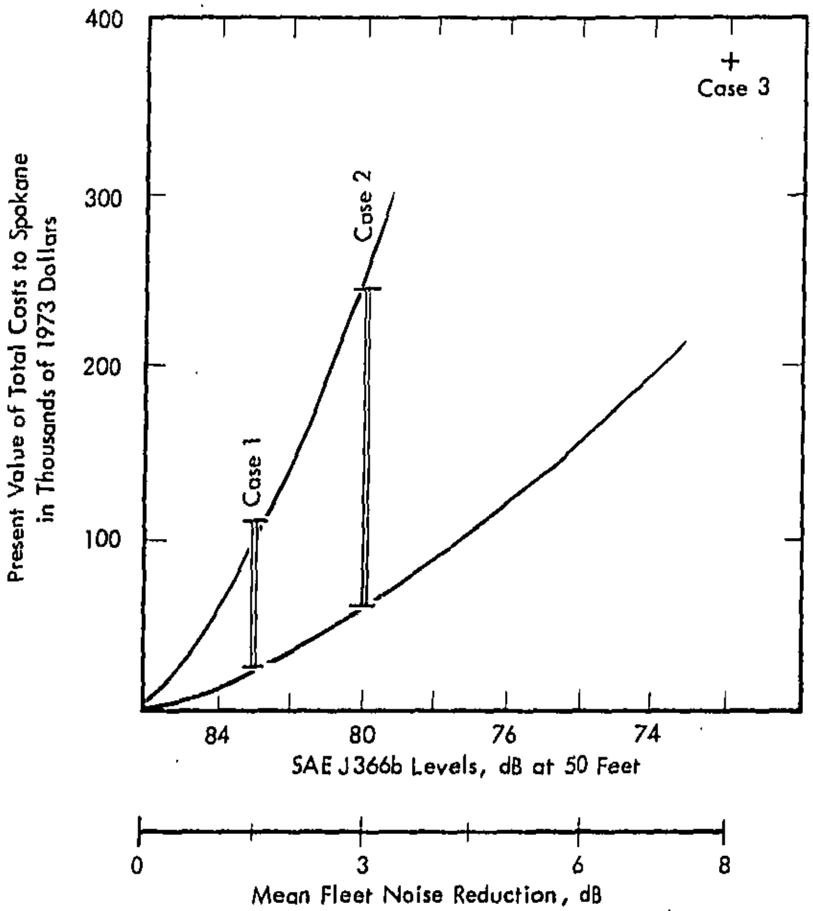

Figure 7.6-2. Present Value of Total Costs for Commercial Buses Versus Mean Low Speed Noise Reduction [Case of Tripled Retrofit Hardware: Multiply Cost Functions Shown by 1.43]

7.7 On-Line Railroad Noise Reduction

As discussed in Section 6.5, the only technically feasible method for reducing on-line railroad noise emission for the 1978 time period has been determined to be the retrofit of the existing freight and passenger diesel electric locomotive fleet with engine exhaust mufflers and quieter cooling fans. It has been estimated that incorporation of these techniques will reduce the noise emitted by the locomotive on passby on the order of 5 to 6 dB and hence, the overall noise exposure from railroad line operations by approximately 3 dB (the locomotive component constitutes roughly one-half the noise exposure energy in a train passby). Analysis of such techniques for quieting the wheel/rail freight- and passenger-car noise components as wheel and track trueing and grinding and general incorporation of all welded mainline track has been shown to yield questionable levels of noise reduction at undefined levels of cost. Also, the curfewing of nighttime train operations, although a potentially effective means of greatly reducing noise exposure, would create such havoc with the mode of operation of the railroad business, that such countermeasures were categorically rejected as unfeasible.

The allocation of locomotives to be so treated in the Spokane analysis is based upon the total number of diesel-electric locomotives in the U.S. factored by the percentage of mainline mileage in Washington State to yield the number of locomotives charged to Washington. This value is then factored by the population of Spokane County over the Washington State population as shown below:

$$\begin{pmatrix}\text{Number of Locomotives}\\ \text{Allocated to Spokane}\end{pmatrix} = \begin{pmatrix}\text{Total Number of}\\ \text{Diesel-Electric}\\ \text{Locomotices in U.S.}\end{pmatrix}\begin{pmatrix}\text{Percentage of}\\ \text{Mainline Track}\\ \text{in Washington}\\ \text{to Total U.S.}\end{pmatrix}\left(\frac{\text{Population of Spokane County}}{\text{Total Washington Population}}\right)$$

$$= (26{,}720^{*})(2.38\%^{*})\left(\frac{283{,}077^{**}}{3{,}352{,}892^{**}}\right) = 54 \qquad (7\text{-}16)$$

*Source: Ref. A3
**Source: Ref. U1

The railroad industry has estimated that the cost to the industry per locomotive treated, including hardware, custom installation, labor and lost revenue due to downtime will range from $5400 for locomotives equipped with standard dynamic braking systems (about 10 percent of the fleet) to approximately $10,400 for locomotives equipped with extended range dynamic braking systems[S3,A2] (87.5 percent of the fleet). Additionally, these sources have reported that, although no actual performance data exists to date on in-service application of the proposed retrofit muffler/fan packages, a one (1) percent increase in fuel consumption is expected. Based upon the industry claim[A3] that this would constitute an $11.6 million annual increase in fuel costs, an annual increase in operating cost of $434 per locomotive is anticipated. Other cost penalties of the retrofit packages in terms of increased maintenance, reliability deterioration, decreased useful life are only speculative at this time and cannot be quantitatively evaluated.

For purposes of this analysis, we are only considering retrofit costs to the existing fleet, as new diesel locomotive production constitutes a low percentage of the national fleet and the rate of growth has been assumed zero.[A3]

Thus, we may proceed with the fleet retrofit analysis, assuming a 5-year compliance period at a rate of 54/5 = 11 locomotives per year as summarized in Table 7.7-1.

Hence, the present value of first costs to achieve a 6 dB locomotive noise reduction through a muffler/fan retrofit package = ($5400 to $10,400)(45.9: Discounted Number of Units) = $248,000 to $477,000.

The present value of operating costs is computed assuming a remaining useful life of locomotives of 15 years[S3] by computing first the present value of increased operating costs per unit, and then multiplying this value by the total discounted number of units:

Table 7.7-1

Determination of Discounted Number of Locomotives Requiring Noise Reduction Retrofit

Year	Number of Locomotives Retrofitted	PV Discount Factor at 10 Percent	Discounted Number of Units Treated
1973	11	1.0	11
1974	11	.909	10
1975	11	.826	9.1
1976	11	.751	8.3
1977	11	.683	7.5
Total	55	4.17	45.9

$$\begin{pmatrix}\text{PV of Increased} \\ \text{Operating Cost} \\ \text{Per Unit}\end{pmatrix} = (\$434/\text{Year})\begin{pmatrix}\text{PV} \\ i = 10\% \\ N = 15 \text{ Years}\end{pmatrix}$$

$$= (434)(7.606) = \$3300/\text{Unit}$$

$$\begin{pmatrix}\text{Total PV of} \\ \text{Increased operating} \\ \text{costs for fleet}\end{pmatrix} = (\$3300/\text{unit})(45.9\text{: Discounted number of units})$$

$$= \$151,000 \qquad (7\text{-}17)$$

Thus, the total cost of retrofit of the Spokane locomotive fleet equals total first costs plus total increased operating costs:

($248,000 to $477,000) + ($151,000) = <u>$399,000 to $628,000</u>

7.8 COMMERCIAL AIRCRAFT NOISE REDUCTION

The following sections develop the present value cost analysis for the four areas of aircraft noise reduction countermeasures defined in Section 6.6.7.

7.8.1 Two-Segment Approach into Spokane International Airport

The two-segment approach may significantly reduce the level of noise exposure in the proximity of the airport beneath the glide path due to the aircraft approaching at a higher altitude on typically a 5.5 to 6 degree glide slope and then intersecting the normal 3 degree glide slope much closer to the airport. To accomplish this maneuver, both additional airborne and ground avionic equipment is required. The price range for the aircraft avionic equipment has been estimated at \$9000 to \$40,000 per aircraft treated[C6] with the ground equipment estimated in the range of \$40,000 per runway. The present value of total cost to the U.S. to implement a 6°/3° approach system into major jet airports has been estimated at \$75 million (1974 dollars).[B1] A conversion factor of .909 has been used to reduce this total cost to 1973 dollars: $75 \times 10^6 \times .909 = 68.2 \times 10^6$ 1973 dollars. The fraction of this total charged to Spokane is based upon a summary of aircraft operations at the top 100 U.S. airports compiled by the FAA[U7] which indicated that Spokane International operations constituted 0.32 percent of the nation's total. Hence, the total first cost to Spokane is:

$$(\$68.2 \times 10^6)(.32\%) = \$220,000$$

It is assumed that this equipment has a useful life of 15 years; thus, by the formulation for computation of the present value of all recurring cycle costs presented in Section 7.1, we may compute this component as follows:

$$PV(CC) = \frac{1}{kr}(CC), \qquad (7\text{-}18)$$

where

k = 10% discount rate

r = 15 years

and CC = the recurring cycle cost of \$220,000 every 15 years

Thus, the present value of cycle costs is:

$$PV(CC) = \frac{1}{(0.10)(15)} (\$220,000) = \$147,000$$

and the total assignable cost to Spokane = First Cost + Present Value of Subsequent Cycle Costs = \$220,000 + \$147,000 = \$367,000.

7.8.2 Quiet Nacelle Retrofit of Existing Aircraft

In the cost analysis of aircraft engine retrofit by incorporating a SAM (sound absorbing material) quiet-nacelle package to all JT8D and JT3D turbofan jet-engined commercial aircraft, we are considering only the first costs for the retrofit treatment. It is assumed that new generation aircraft (i.e., DC-10, L-1011) which will replace the retrofitted aircraft upon their retirement will not incur a cost penalty for quieter operation in terms of either increased acquisition costs nor increased operating costs.

The total cost to the U.S. again in terms of present value of 1974 dollars discounted at 10 percent for the 8D/3D SAM retrofit program has been estimated at \$635 million.[C6] Adjusting this value to 1973 dollars as before yields: $(\$635 \times 10^6)(.909) = \$577 \times 10^6$. Again, factoring this total cost by the percentage of commercial jet operations occurring at Spokane International Airport yields:

$$(\$577 \times 10^6)(.32\%) = \$1.85 \times 10^6 \text{ 1973 dollars}$$

7.8.3 Aircraft Rerouting to Avoid Densely-Populated Areas

In considering costs to reroute aircraft away from densely-populated areas of the city, we are concerned only with approach activity into runway 21 and departures emanating from runway 03 (see map, Appendix B). The only costs assessed are in the form of increased annual operating costs of equipment, crew and additional fuel (i.e., the Direct Operating Costs - DOC) resulting from the aircraft having to travel an added distance due to the reroute (added distance for the Spokane analysis amounts to 15.1 n mi per flight or an additional 5.04 minutes of flight time per flight) (see Figure 7.8-1).

The number of flights per day occurring over the city by type of equipment and total increases in direct operating costs are summarized in Table 7.8-1.

Table 7.8-1
Summary of Increased Direct Operating Costs (DOC) for Aircraft Rerouting

Equipment	Flights/Day[(1)] Takeoff and Landing	1974 DOC[(2)] ~ $/Hr	Δ$/Yr (Reroute)
707-320B	1.89	931*	53,950
DC-10-10	.87	885	23,606
F-101	41.4	0**	-
DC-9	12.12	549	204,008
727	12.5	735	281,689
Totals	68.8		563,000

*DC-8 DOC data used - is assumed nearly identical to 707-320B.

**These are military training flights; therefore, it has been assumed that rerouting will not affect costs.

(1) Official Airline Guide, August 1974.

(2) R. Dixon Speas Associates Report, subcontract to Reference B1. Costs adjusted to reflect conditions for the same period (1974) utilized in the first column.

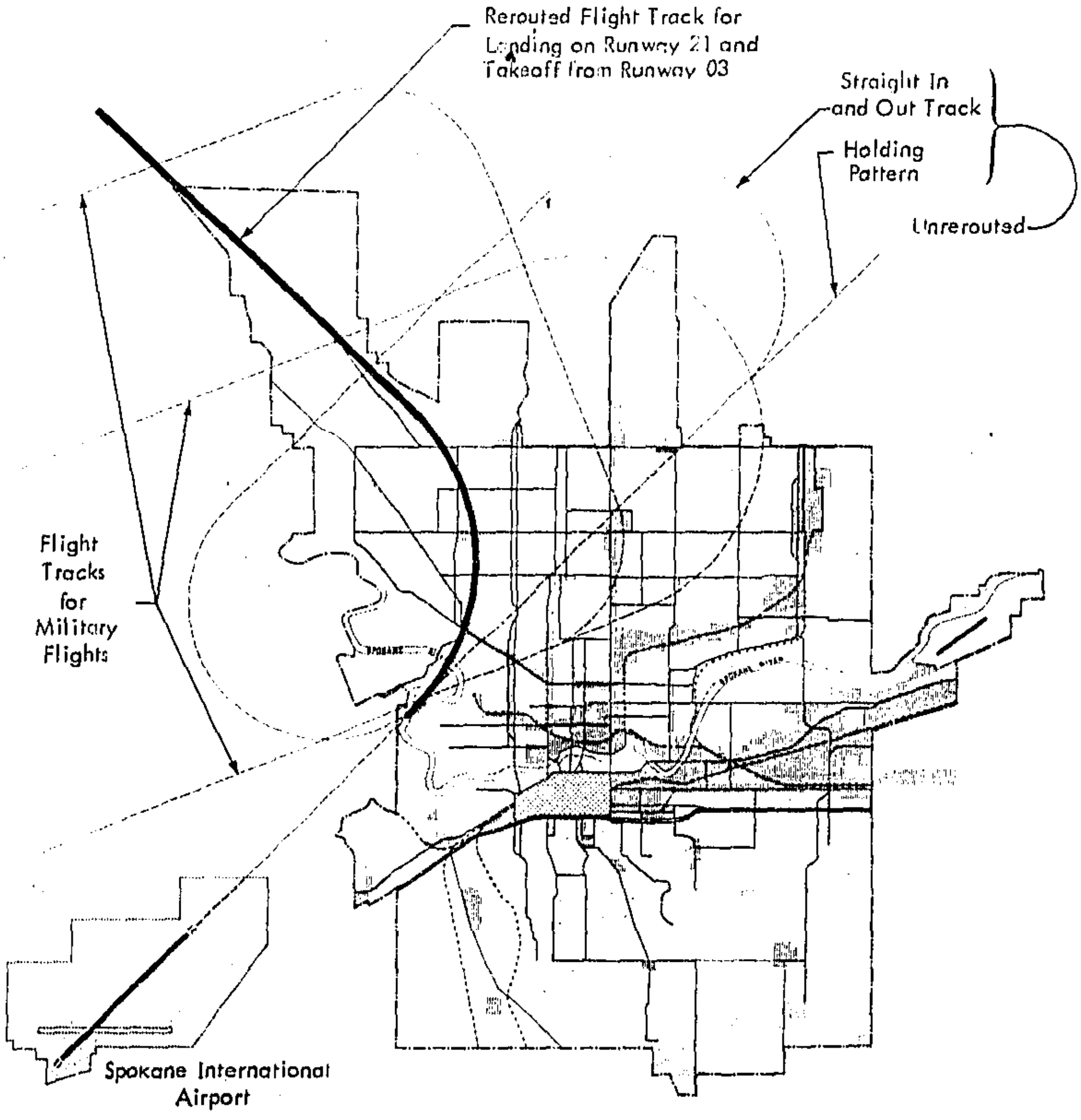

Figure 7.8-1. Map of City of Spokane, Washington, Showing Rerouted Flight Track (Note that No Holding Pattern is Flown Over the City).

While we do anticipate changes in the aircraft fleet over the years, and hence, changes in the DOCs of the fleet flying in the future, as a first approximation of present value of all increased operating costs, it has been assumed that the annual total cost developed in Table 7.8-1 will continue to occur so long as this option is exercised. Hence,

$$\begin{pmatrix} \text{Present Value of} \\ \text{Increased Operating} \\ \text{Costs due to Rerouting} \end{pmatrix} = (\$563{,}000/\text{year}) \begin{pmatrix} PV \\ i = 10\% \\ n = \infty \end{pmatrix}$$

$$= (\$563{,}000)(10) = \$5.63 \times 10^6 \text{ dollars} \qquad (7\text{-}19)$$

7.8.4 Night Curfew

An analysis of night flight operations at Spokane International Airport indicates that the only effective curfew (in that there are currently only a very few night operations) involves curtailment of service to Seattle by elimination of one flight per day. The net effect is to reduce service to Seattle from 11 to 10 flights per day by elimination of the one night operation. This reduction in service results in a "frequency delay" incurred by the scheduled flight not coinciding with a traveler's departure time.

A functional relationship (empirical) has been developed by Douglas for frequency delay as expressed by:[D6]

$$T_f = 92\, F^{-.456} \qquad (7\text{-}20)$$

where

T_f = expected frequency delay per passenger in minutes

F = daily flight frequency (number of flights/day)

Thus, reducing Seattle departures from 11 to 10 flights per day results in a frequency delay computed as follows:

$$\Delta T_f = 92(10^{-.456} - 11^{-.456}) = 1.37 \text{ minutes/passenger}$$

It is next necessary to estimate the average daily number of Seattle-bound passengers on the remaining 10 flights so that the total daily delay may be computed. These flights in terms of type of equipment available, number of seats and typical load factors are summarized in Table 7.8-2.

Table 7.8-2

Summary of Seattle-Bound Passenger Movements

Equipment Type	Average Number of Daily Operations to Seattle	Typical Seating Capacity	Average Load Factor*	Number of Passenger Movements
DC-10	1	270	.511	138
707	2	147	.511	150
DC-9	4	56	.5	112
727	3	163	.658	322
Totals	10	-	-	822

*Source: Aviation Week and Space Technology, June 1974. Itemized as follows: United Airlines: 658, Northwest: 511, AirWest: assumed at .5.

Thus, the total resultant daily passenger delay is:

(1.37 minutes/passenger) (822 passengers/day) = 1126 minutes/day

or 365 x 1126 = 411,000 minutes per year. (7-21)

Finally, we need to assign a value to this lost travel time to arrive at the total increased cost per year. To evaluate the value of travel time, we assume this is comparable to the traveler's average earning rate per hour while on the job. Thus, an analysis of the mean incomes of air travelers (derived from the 1972 U.S. Census of Transportation) as presented below in Table 7.8-3 yields a mean income for air travelers of $16,000/year or approximately $8.00/hour.

Table 7.8-3

Summary of Mean Incomes of Commercial Air Travelers

Family Income	Number of Person-Trips (1972) (Thousands)
< 5,000	2,986
5,000 - 7,499	3,481
7,500 - 9,999	4,504
10,000 - 14,999	14,103
> 15,000 (Used: 20,000)	26,019
Average Income for Air Travelers	16,000

Thus, the total cost of curfew is:

$$\left(\frac{411,000}{60}\ \frac{\text{hours}}{\text{year}}\right)(\$8.00/\text{hour}) = \$54,800 \text{ per year} \qquad (7\text{-}22)$$

Finally, the present value of curfew costs if continued over the conceivable future is:

$$\begin{pmatrix}\text{Present Value of Lost} \\ \text{Travel Time Resulting} \\ \text{from Frequency Delay}\end{pmatrix} = (\$54,800)\begin{pmatrix}PV \\ i = 10\% \\ n = \infty\end{pmatrix} \qquad (7\text{-}23)$$

$$= (54,800)(10) = \$548,000$$

7.9 PATH-RECEIVER TREATMENTS

7.9.1 Dwelling Sound Insulation

We consider the costs for dwelling sound improvement as we would a recurring cycle cost which accrues every 30 years (assumed life of a residential or commercial structure). Thus, the present value of total costs associated with this countermeasure may be computed as follows from Eq. (7-24):

$$\begin{pmatrix} \text{PV of} \\ \text{Total} \\ \text{Cost} \end{pmatrix} = \begin{pmatrix} \text{Total Cost of} \\ \text{Modification} \end{pmatrix} \left(1 + \frac{1}{ni}\right) \qquad (7\text{-}24)$$

where

n = 30 years

and i = 10 percent discount rate

The assumption that the costs of sound insulating subsequent structures (30 years hence) is identical to the costs of modifying an existing dwelling is admittedly somewhat conservative. However, due to the uncertainties in estimating future construction costs, it is not unreasonable. The total cost to modify the existing structure is determined from the cost/ft^2 of treatment required to achieve the desired improved noise level reduction as given in Section 6.7.1 multiplied by the square footage of the structure receiving treatment as determined by the techniques given in Section 7.9.3. This costing does not include consideration of any increases in home or commercial fuel consumption resulting from increased energy utilization due to the incorporation of air conditioning systems required in the process of sound insulation improvements. This may be partially counterbalanced in areas with a rough climate by the improved heat insulation which most often results as a side-benefit from an upgraded sound insulation.

7.9.2 Barriers

The costing of the implementation of barriers for highway or railroad noise reduction is conducted in a manner identical to that of dwelling sound insulation.

An effective life of 50 years is assumed.[C2] Hence, the costing analysis is as follows:

$$\begin{pmatrix} \text{PV of} \\ \text{Total Cost} \end{pmatrix} = \begin{pmatrix} \text{Initial Direct} \\ \text{Cost of} \\ \text{Barrier} \end{pmatrix} + \frac{1}{ni} \text{ (Replacement Cost)} \qquad (7\text{-}25)$$

where

n = 50 years

and i = 10 percent

The development of these costs for the barrier heights considered in the Spokane analysis is summarized in Table 7.9-1 below.

Table 7.9-1

Cost of Barriers

Barrier Height Feet	Application	First Cost Per Lineal Foot	Useful Life Years	Present Value Factor for Subsequent Cycle Costs: $\frac{1}{ni}$	PV of Total Costs Per Lineal Foot
10	Highway	$ 44	50	.2	$ 53
15	Highway/ Railroad	$ 66	50	.2	$ 79
20	Railroad	$100	50	.2	$120

7.9.3 Land Acquisition

The total cost of land acquisition consists of the sum of the direct acquisition costs of the affected property and the relocation costs of individuals. Hence, we may define the costs involved in land acquisition as follows:

1. Loss of value of property improvements; however, basic land value remains unaffected.

2. Payments made to homeowners or renters for relocation expenses (under the precedent established in the Federal-Aid Highway Act of 1968).

It has been determined that property values reported by property owners in the 1970 census were an appropriate valuation of the property.[W1] These total values then need to be inflated to 1973 dollars by incorporation of a factor of 1.19 (representing an average increase in costs/ft^2 of residential construction from 1970 to 1973 as determined from Reference N1). We must next determine what portion of this total value in 1973 dollars is lost by the land acquisition. This may be obtained by first considering the number of rooms in the dwelling being acquired (as reported in the 1970 U.S. Census). Next, we must establish an average room size for the dwelling acquired to yield the total amount of living area the use of which will be lost. Two approaches to this analysis are considered. In the first, the reported property value (in 1970 dollars) is plotted versus number of rooms in the dwelling for the homes in the 1970 Spokane Census Tract #19 which is deemed representative of the type of land that would conceivably be acquired by virtue of its proximity to a busy traffic arterial. The data points, though somewhat scattered (as indicated in Figure 7.9-1), clearly indicate the expected result that the value of the property may be generally assumed to increase with the number of rooms in the dwelling. Here, a rather arbitrary choice of typical room size versus total property valuation is made. It is assumed that the more expensive home have larger rooms, albeit, a larger number of rooms as well. It is assumed that a \$25,000 home would have a total living area of approximately 2000 ft^2. This corresponds to an average number of rooms of 9.5 (observing the central tendency of the linear data fit in Figure 7.9-1) thus yielding an average room size for the \$25,000+ home of 210 ft^2. Similarly, a \$10,000 home is estimated to have an average room size of 150 ft^2. Thus, using these end points, the empirical relationship between average room size and total property value (in 1970 dollars) may be developed as:

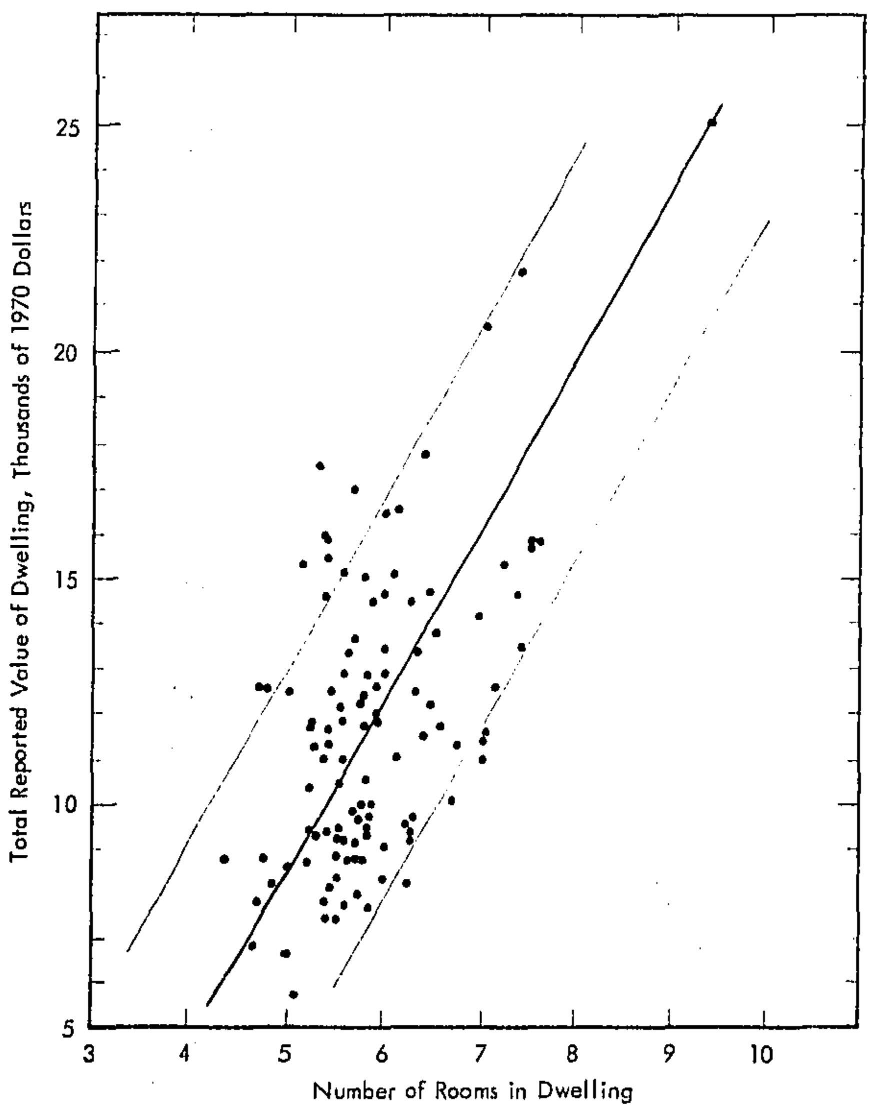

Figure 7.9-1. Distribution of Homes in Census Tract Adjacent to Busy Arterial Roadway (1970 Spokane, Washington, Census Tract Number 19).

$$
\left.\begin{aligned}
SR &= 150 \text{ ft}^2 \text{ for } V \leq 10 \\
SR &= 210 \text{ ft}^2 \text{ for } V < 25 \\
SR &= 150 + 4(V - 10) \text{ ft}^2
\end{aligned}\right\} \qquad (7\text{-}26)
$$

where SR = average room size,

V = total valuation in thousands of 1970 dollars.

Thus, the value of improvements in 1973 dollars could be determined from the following formula:

$$
\begin{aligned}
&\text{Land Value} = (\text{Total Property Value} - I) \times 1.19 \\
&1.19 = \text{Conversion Factor to 1973 Dollars}
\end{aligned} \qquad (7\text{-}27)
$$

where I = Improvement Value = Number of Rooms (from 1970 U.S. Census) x SR x \$16.43

\$16.43 = average cost in 1970 dollars per ft^2 (from Reference N1).

A second and somewhat more direct method of establishing the relationship of the improvement value to the total property value is based upon a survey of assessed land values conducted during the course of the program by a Spokane-based firm of a broad (but random) sample of homes judged to be "candidates" for acquisition by virtue of their locations relative to major roadways and railroad tracks. The results of this 22 location survey indicated a mean ratio of improvement value to total assessed property valuation of .18 with a standard deviation of .12, thus yielding a mean + 1 σ value of .30. This indicates that for the majority of properties surveyed, the improvement value would be ≤30 percent of the total reported value. This survey also yielded a mean value of \$11.50/ft^2 with a standard deviation of \$5.90/ft^2. Thus, the mean + 1 σ = \$17.40/ft^2 would be a conservative estimate of the improvement value.

In that the latter of these two approaches is based upon an actual survey of typical "acquirable" properties in the City of Spokane, it is selected for use in the final analysis. It is interesting to note that the average room size for the selected survey sample is 171 ft^2 and the average total property value in this sample is $14,116. The previously developed empirical formula for room size yields 166.5 ft^2, agreeing to within 2.5 percent with 171 ft^2.

We need to consider next the compensation paid to displaced persons. According to the Uniform Relocation Assistance and Real Property Acquisition Policies Act of 1970, homeowners can receive up to $15,000 and tenants up to $4000 over a 4 year period as compensation for relocation. An average of $2800 was paid out to homeowners who were displaced by highways in 1971.[X1] Inflating this value to 1973 dollars, assuming an 8.4 percent increase in costs of services from 1971 to 1973*, yields an equivalent compensation in 1973 dollars of $3035 per household. Based upon the fact that rental units typically are 25 percent smaller (occupy 25 percent less floor area than owner occupied homes),[W1] it is assumed that this compensation is 1.33 times as large as that received by renters. Thus, compensation paid to renters is estimated at $2282 per household.

We may summarize the costs associated with relocation as being one-time-only direct costs which amount to the value of property improvements cost as previously discussed plus $3035 for homeowners or $2282 for renters.

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*Consumer Price Index, Services Component; 1971: 130.8, 1973: 141.8, ratio: 1.084

CHAPTER 8

NOISE COUNTERMEASURE COST-EFFECTIVENESS ANALYSIS OF THE EXPERIMENTAL CITY: SPOKANE, WASHINGTON*

8.1 INTRODUCTION

The community noise countermeasure analysis was computerized and carried out on an actual experimental city: Spokane, Washington. Appendix A discusses the philosophy for city selection and how Spokane became the final choice (for a map, see end of Appendix B).

It should be noted that while a considerable amount of effort was expended in selecting Spokane, Washington, with a noise exposure typical of a broad range of U.S. cities; each city has its own peculiarities and unique characteristics which may influence the dominance of particular noise sources. In Spokane, for example, there are more miles of main line railroad track than there are freeway miles and, in fact, there is only one freeway which divides the City into two segments. The sample selected for analysis attempts to provide representative noise exposure from all major sources, but it must be remembered that this noise exposure is unique to Spokane. Hence, it is important to consider these practical limitations on the analysis conducted on Spokane. One should not attempt to extend the results obtained directly to the Nation as a whole or to other cities which differ substantially in size, geographic structure, commercial and industrial activity, and demographic characteristics from that of Spokane.

At the end of Chapter 2, the Noise Impact Index (NII) was introduced as the basic composite index for rating the desirability of a given noise environment. Three types of basic information are required to evaluate Eq. (2-8):

- Transfer functions relating noise levels to human response (Chapter 3).

*All relative and absolute sound levels in dB are A-weighted levels unless otherwise specified.

- The population distributions for day and night and different land use categories. How these were obtained is outlined in Appendix B. How the population is grouped into noise exposure cells is discussed in the latter portion of Appendix C.

- The spatial and temporal distribution, and the strength of noise sources. Chapter 4 gives data on time and strength distribution in general. Appendix B discusses how the particular information for Spokane was obtained. Chapter 6 presents feasible countermeasures for reduction of the noise level of these sources, and Chapter 7 presents the present value cost analysis of these countermeasures.

This vast amount of data has been processed by a Wyle-developed computer program, a short description of which is given in Appendix D.

The objective of the analysis conducted is to determine the most cost-effective (here referred to as "optimum") set of noise reduction countermeasures such that a minimal NII results, given the constraint of a fixed amount of funds. Stated in other words: The problem is to determine a scenario of expenditures on noise reduction which provides, on the average, the greatest reduction in outdoor noise for the greatest number of people. For many of the scenarios, cost-effectiveness was determined for low, medium, or high ranges of estimated costs for most of the countermeasures.

The cost-effectiveness analysis conducted for Spokane is structured such that, in addition to the primary task of determination of optimum expenditures on countermeasures for community noise reduction, the city modeling process is refined and systematically simplified. In this process, both the shape and the location of the end points of the exposure-human response transfer functions are evaluated as to their effects on the program results. A supplementary analysis of selected segments of Spokane is conducted, using a second noise exposure metric (the Noise Pollution Level), in order to support the results obtained using the Energy Equivalent Level.

8.2 METHOD OF ANALYSIS

8.2.1 Rank Ordering of Community Noise Sources

The initial analysis of Spokane is conducted on a continuous segment encompassing about one-third the area of the city (Figure 8.2-1), containing the entire Central Business District (CBD) and approximately two-thirds of the daytime population, and comprising 808 noise exposure cells. This segment includes the effects of freeway traffic, railroad operations through town, commercial and military aircraft operations, as well as arterial and local road traffic. Additionally, buses in the CBD are treated as distinct noise sources.

The computer program has been designed to provide the relative ranking of the noise sources in order of severity of noise impact for the 1973 and 1978 baseline cases (baseline means that no funds are expended on noise countermeasures). This is obtained by computing the contribution of each source to NII. The result is given in Table 8.2-1. It may be observed that automobile and heavy trucks constitute the two most significant sources for both 1973 and 1978, followed by commercial and military aircraft operations.

From 1973 to 1978, the ordering of the sources shifts slightly. This change in relative significance results from two factors: the first being the growth of both the population (or number of people exposed to noise) and the growth of the number of noise-producing sources; secondly, in the 5-year period between 1973 and 1978, the automobile and truck fleets will have been largely (57 percent and 47 percent respectively) replaced by newer, quieter units, hence, in essence stabilizing the total noise impact situation for Spokane. The overall effect of quieter new production units is more significant for the heavy truck population than for automobiles (primarily because automobiles exhibit considerably less noise than trucks); hence, the number one and two rank positions shift between the 1973 and 1978 cases,

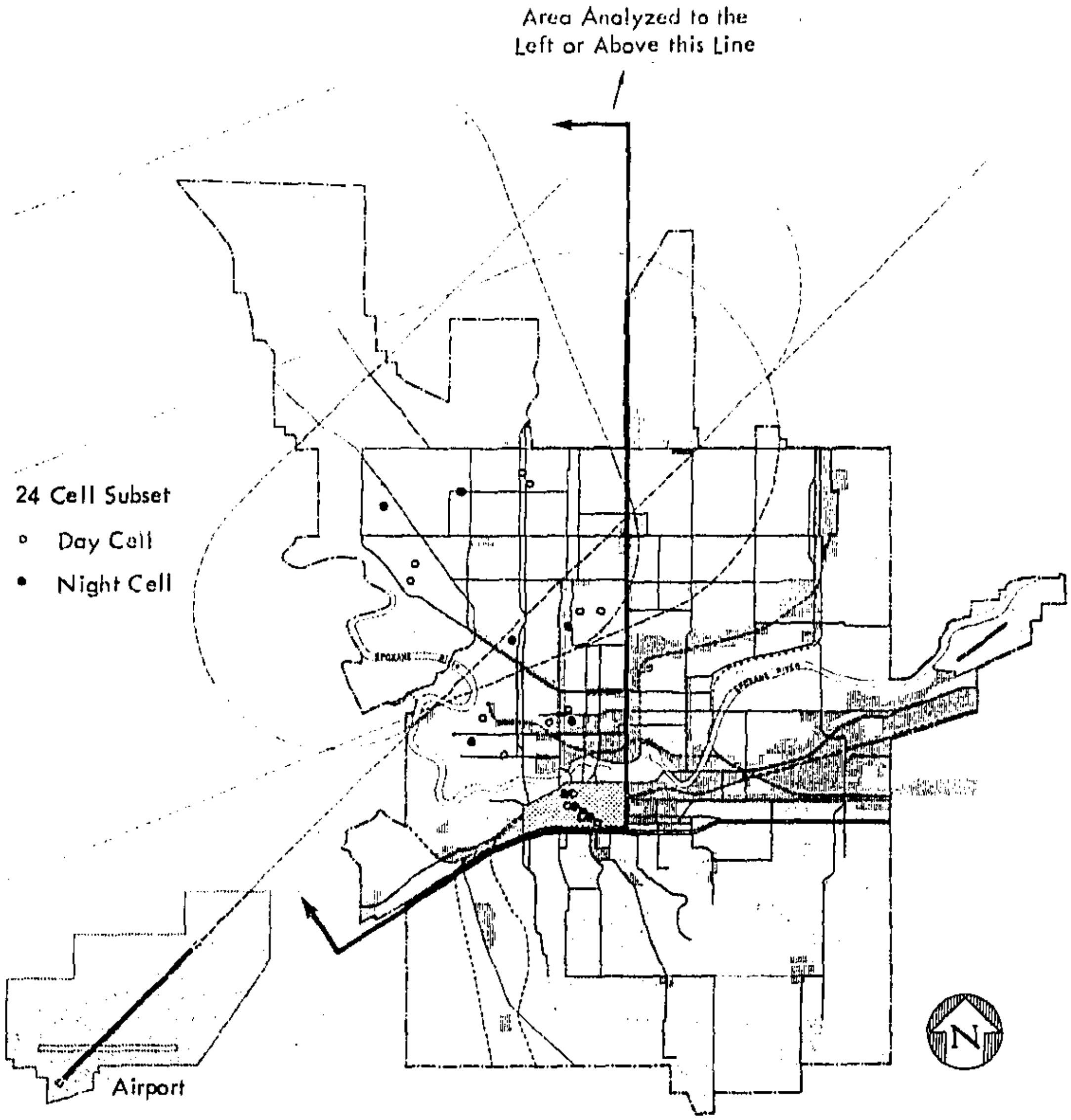

Figure 8.2-1: Identification of One-Third Segment and 24 Cell Subset of Spokane, Washington, Utilized in the Optimizing Noise Countermeasure Analysis (See Also Map in Appendix B).

Table 8.2-1

Relative Rank Ordering of Dominant Community Noise Sources for Spokane, Washington, for the Baseline 1973 and 1978 Cases (Based Upon Linear Noise Exposure-Adverse Response Transfer Functions)

Environmental Noise Source Identification	Baseline Source Ranking		NII Contribution	
	1973	1978	1973	1978
1. Automobiles on Arterials	2	1	.0786	.0874
2. Trucks on Arterials	1	2	.0831	.0727
3. Local Traffic	10	9	.0002	.0007
4. Military Aircraft Operations	4	4	.0506	.0517
5. Commercial Aircraft Operations	3	3	.0653	.0687
6. Automobile Tires on Freeways	7	8	.0128	.0136
7. Truck Tires on Freeways	6	6	.0137	.0145
8. Freight Trains	5	5	.0207	.0224
9. Passenger Trains	9	10	.0062	0
10. Buses in Central Business District	8	7	.0127	.0141
Total Noise Impact Index			.3440	.3458

leaving automobile traffic on arterials as the most pervasive source of community noise by the 1978 time period. The other changes in rank ordering are not significant.

8.2.2 24-Cell Subset Representation of the One-Third City Segment

In order to verify that the noise exposure of the experimental city could be accurately determined by a scaled down model which would greatly reduce the amount of required input data and expedite data processing, an analysis of a 24-cell subset of the full one-third city segment has been carried out.

The 24 cells are selected such as to be representative of the noise exposure characteristics of the full segment. Since the computer program calculates a noise annoyance index for each cell, it is necessary to maintain the proper distribution of population for each land use type. Furthermore. it is necessary to maintain a balance with regard to levels of noise exposure by the various types of noise sources.

The approximate population distribution percentages by land use category for the full one-third segment (see also Appendix C, Table C-1) are shown in Table 8.2-2.

Table 8.2-2

Population Distribution Percentages by Land Use Category for Northwest Third of City of Spokane (Daytime)

R 1	26 Percent
R 3	10 Percent
R 4	8 Percent
Central Business District	48 Percent
Schools	8 Percent

In the 24 cell subset, a sample population is selected of approximately 10,000 which are distributed within a number of cells of the proper distribution of population by land use type. Cells are chosen of the various land use types from the master data file with relative populations determined by the table above. To maximize efficiency, cells with large populations receive primary consideration.

Furthermore, a candidate cell is required to exhibit component source levels typical of its land use type. Within each land use type the set of cells as a whole is representative with respect to noise exposure of all the cells of that type in the northwest third of Spokane. These cells are selected by judicial inspection of the land use map and overlayed noise exposure contours for individual sources.

The above cell definition procedure is carried out twice, once for daytime and once for nighttime. The cells so chosen are identified in Figure 8.2-1.

Scenarios of money optimally spent on noise countermeasures are for three different amounts of total funds available: 5, 10, and 30 million 1973 dollars. The usual procedure of arriving at a scenario is to start at the "baseline" case, i.e., computing the NII for no money spent at all. Then, money is spent incrementally such as to always decrease NII in the most efficient way, i.e., spend additional funds on that countermeasure which will decrease NII the most. Because there is a limit in most countermeasures of how much noise reduction is technically feasible by the target year 1978, the amount of funds that can be expended on any one countermeasure is limited. In some cases, this limit is attained very quickly, in others, never. For instance, it will be seen later in this chapter that for the Spokane analysis, it is highly productive to spend money on city bus noise reduction to the limit, whereas the limit in the category of path-receiver treatments (including relocation of residents) is so high that it is never reached. When this analysis is conducted for the 1978 time period for the baseline case and three levels of expenditures on noise countermeasures, the results given in Table 8.2-3 are obtained. All three cost functions are used (low, medium, and high; see beginning of Chapter 7). For the cases with expenditures, the NII values are of course associated with an optimal distribution of funds. A correction is carried out by dividing the NII's for the 24-cell subset by 1.062. This value represents the ratio of the 24-cell NII to the full third segment NII for the baseline 1978 case. Table 8.2-3 is shown in graphical form in Figure 8.2-2.

The percent deviation between the corrected 24- cell results and the full segment is shown to range from 1.4 to 5.3 percent at 5 million, and up to 7.6 percent at $10 million. For these levels of expenditure, the majority of effort toward noise reduction is oriented toward reductions of the source itself and limited treatment of the path or receiver in the form of barriers, home sound insulation or relocation of the

Table 8.2-3

Noise Impact Index for 5, 10, and 30 Million Dollar Total Expenditures on Spokane, Washington, Using Full and Partial Segment Analysis (Linear Noise Exposure - Adverse Response Transfer Functions)

Range of Cost Function	Segment Analyzed	Noise Impact Index for Specified Levels of Expenditure in Millions of Dollars			
		Base – 1978	5	10	30
Low	Full	.324	.265	.234	.200
	24 Cell	.344	.297	.267	.251
	24-Cell – Corrected	.324	.279	.251	.236
	Percent Deviation	0	5.3	7.3	18.0
Medium	Full	.324	.291		
	24 Cell	.344	.313	.280	.264
	24-Cell – Corrected	.324	.295	.264	.249
	Percent Deviation	0	1.4		
High	Full	.324			.217
	24 Cell	.344	.322	.285	.267
	24-Cell – Corrected	.324	.303	.268	.251
	Percent Deviation	0			15.7

receiver away from the local dominant source (a more detailed explanation of the relative expenditures by countermeasure will be given later on in this chapter). At the $30 million level of expenditure, the deviation is higher, ranging up to 18 percent. This divergence at the higher levels of expenditure is also seen in Figure 8.2-2. It results from the 24-cell analysis through modeling limitations: a point of diminishing return is reached in terms of expenditures on path or receiver noise reduction due to the limited number of dwellings and barrier location possibilities within the small subset. Hence, the analysis yields negligible improvement in total impact

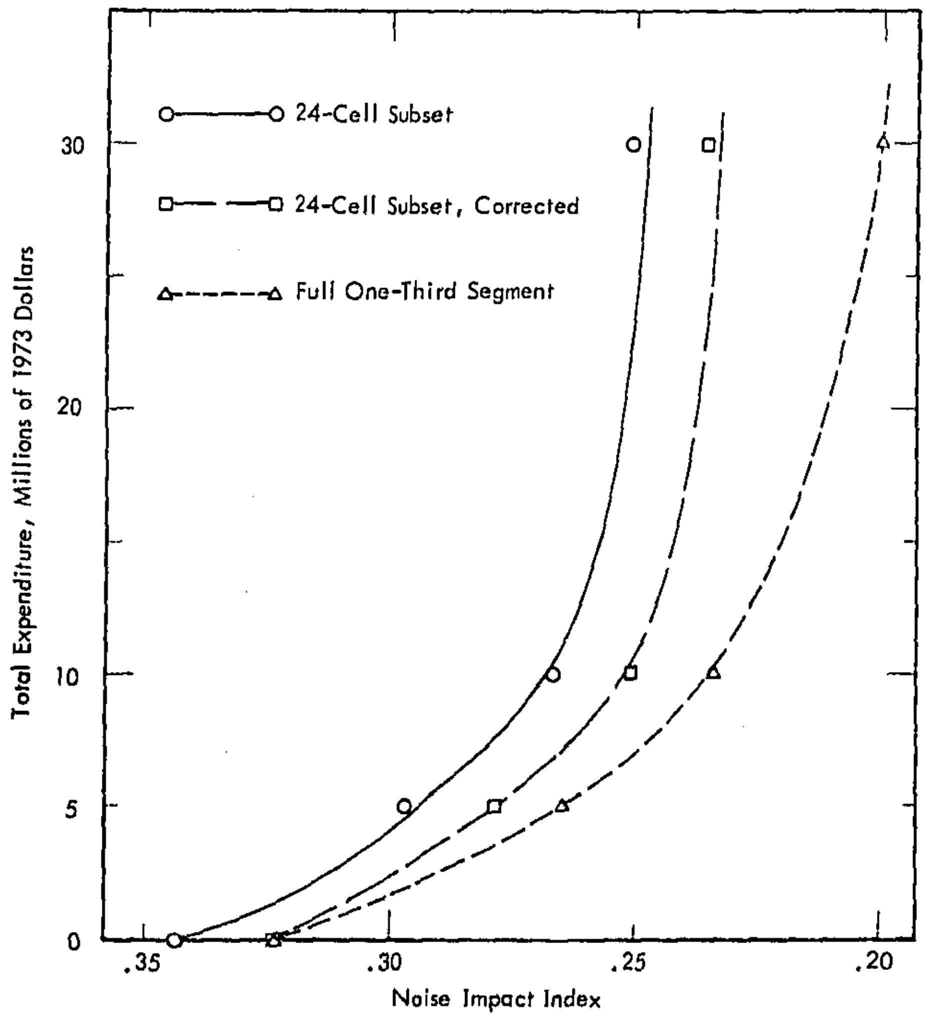

Figure 8.2-2. Noise Impact Index for Optimum Expenditure Scenarios, Total Expenditure Varying, Linear Noise Exposure - Adverse Response Transfer Functions, Low Range of Costs Versus Noise Reduction Functions. Comparison of Full One-Third Segment of City of Spokane with 24-Cell Subset. See Text for Meaning of "Corrected."

(the NII) for additional expenditure. The full segment, giving a more accurate portrayal of the noise reduction possibilities due to these path or receiver modifications, does not approach the zero incremental return situation quite as rapidly; however, as may be observed by the slopes of the full segment noise reduction versus cost curves in Figure 8.2-2, this point is rapidly being approached. Hence, it may be concluded that the difference between the analysis with only 24 cells versus the results for the full third city segment (808 cells) will probably not exceed 20 percent even at the highest levels of expenditure considered here.

8.2.3 Extension of Analysis to Entire City

Because of the relative success of the above sampling procedure, it is now attempted to model the entire City of Spokane in a similar way. The 24 cells previously selected have component source levels typical of the northwest one-third of the City. The expected component source levels of any one part of the rest of the City can be matched to one or more of the 24 cells chosen earlier.

The task at hand is now to determine population distribution percentages for the entire City and to distribute a sample population among the 24 cells of various land uses and noise exposures accordingly. Determining the population distribution percentages for the rest of the City and combining these with the previously determined percentages for the northwest third of the City, Table 8.2-4 results.

Table 8.2-4

Population Distribution Percentages by Land Use Category for the Entire City of Spokane (Daytime)

R1	42 Percent
R3	9 Percent
R4	9 Percent
Central Business District	32 Percent
Schools	8 Percent

A sample population of 10,000 is then distributed among the 24 cells using the above table as a guideline. Note that this procedure does not require selection of a new group of actual cells, but instead redistributes the population among the existing 24 cells to achieve a proper representation of land use situations.

In addition, it is necessary to examine the component source levels within the cells of each land use type and to distribute the population assigned to that land use type according to the component source levels that any given fraction of the population might experience.

Land use type R 1 is modified the most. A large percentage of the R 1 population in the rest of the City resides in regions of comparatively low exposure to traffic noise. This condition is reflected in the population assignments. Similar considerations are given to railroad noise exposure, aircraft noise exposure, etc. A freeway noise component is added to both R 3 and R 4 land use categories as no such component exists in the 24-cell representation of the northwest one-third of the City. A relatively low level is used to reflect the small number of people who are exposed to freeway noise.

No such modifications are necessary in the CBD as this district is entirely contained in the northwest one-third of the City. However, as per the table above, its relative importance to the entire City decreases somewhat.

Implementing all the above considerations, one would then expect to have a small number of cells which would yield noise exposure characteristics and optimized countermeasure scenarios similar to the 3000 to 5000 cells which would be necessary to completely define the entire City. The sample thus obtained is called the "24 cell full city model."

8.3 RESULTS AND DISCUSSION

The basic results of this study are expressed in terms of dollars expended on various countermeasures and the resultant levels of Noise Impact Index (NII) achieved. It is also possible to estimate the average reduction in noise levels achieved for any given countermeasure by tracing back through the cost estimates for each type of countermeasure as developed in Chapter 7 and the corresponding magnitude of noise reduction achieved from the data in Chapter 6.

8.3.1 Linear Transfer Function Analysis

Table 8.3-1 shows the cases for which an optimum noise countermeasure expenditure scenario has been obtained. The 24-cell third city subset is analyzed in full. Tables 8.3-2 and 8.3-3, and Figures 8.3-1 and 8.3-2 show the results. Comparing this data indicates that, with minor variations, the allocation of funds is identical for each optimized level of total costs giving further evidence of the validity of the 24-cell analysis.

Table 8.3-1

Cases for Which an Optimum Noise Countermeasure Expenditure Scenario Has Been Found (Linear Transfer Functions)

	$5M			$10M			$30M		
	ℓ	m	h	ℓ	m	h	ℓ	m	h
Northwest One-Third of City	x	x		x			x		x
24-Cell One-Third Subset	x	x	x	x	x	x	x	x	x
24-Cell Full City Model		x			x			x	
ℓ = low, m = medium, h = high countermeasure cost functions.									

It should be observed that there may exist more than one combination of countermeasure expenditures that, for the same level of total cost, will yield a minimum Noise Impact Index. The word "minimum" is used in the mathematical sense: The Noise Impact Index may be regarded as a function of many variables, the latter being the expenditures in each countermeasure category. This function may be imagined as a multidimensional

Table 8.3-2

Optimum Noise Countermeasure Expenditure Scenarios,
Northwest One-Third of Spokane, Linear Transfer Functions
Underlined Numbers: Spending Limit Reached

Level of Total Expenditure in Millions of Dollars	Countermeasure Cost Functions	Cost Allocation per Countermeasure in Millions of Dollars										Noise Impact Index
		Automobile Noise Reduction – Low and High Speed	High Speed Heavy Truck Noise – Tires	Low Speed Heavy Truck Noise Reduction	Locomotive Noise Reduction – Freight and Passenger Trains	City Bus Noise Reduction in CBD	Commerical A/C: 6/3 Approach at Spokane International	Commerical A/C: Flight Path Rerouting	Commercial A/C: Quiet Nacelle Retrofit	Commerical A/C: Night Flight Restrictions at Spokane International	Path-Receiver Treatment: Barriers – Home Insulation – Relocation	
Baseline 1978												.3244
5	Low	2.12	0	2.3	0.44	0.14	0	0	0	0	0	.2649
	Medium	3.8	0	0.97	0	0.14	0	0	0.116	0	0	.2914
	High											
10	Low	4.95	0	2.3	0.44	0.25	0.367	0	1.59	0.10	0	.2341
	Medium											
	High											
30	Low	6.83	0	2.3	0.44	0.25	0.367	0.09	1.85	0.05	17.82	.2002
	Medium											
	High	6.82	0	3.35	0.68	0.25	0.367	0.07	1.85	0.05	16.56	.2174

Table 8.3-3

Optimum Noise Countermeasure Expenditure Scenarios
24-Cell Representation of Northwest One-Third of Spokane, Linear Transfer Functions
Underlined Numbers: Spending Limit Reached

Level of Total Expenditure in Millions of Dollars	Countermeasure Cost Functions	Cost Allocation per Countermeasure in Millions of Dollars										Noise Impact Index
		Automobile Noise Reduction - Low and High Speed	High Speed Heavy Truck Noise - Tires	Low Speed Heavy Truck Noise Reduction	Locomotive Noise Reduction - Freight and Passenger Trains	City Bus Noise Reduction in CBD	Commerical A/C: 6/3 Approach at Spokane International	Commerical A/C: Flight Path Rerouting	Commercial A/C: Quiet Nacelle Retrofit	Commerical A/C: Night Flight Restrictions at Spokane International	Path-Receiver Treatment: Barriers - Home Insulation - Relocation	
Baseline 1978												.3440
5	Low	2.12	0	2.3	0.44	0.14	0	0	0	0	0	.2967
	Medium	3.8	0	0.97	0	0.14	0	0	0.116	0	0	.3130
	High	2.4	0	2.25	0	0.14	0	0	0.35	0	0	.3215
10	Low	4.95	0	2.3	0.44	0.25	0.367	0	1.59	0.10	0	.2670
	Medium	4.37	0	2.8	0.56	0.25	0.367	0	1.55	0.10	0	.2801
	High	4.9	0	2.8	0	0.25	0.367	0	1.58	0.10	0	.2849
30	Low	6.85	0	2.3	0.44	0.25	0.367	0.07	1.85	0.05	17.82	.2511
	Medium	6.85	0	2.8	0.56	0.25	0.367	0.04	1.85	0.05	17.21	.2642
	High	6.85	0	3.35	0.68	0.25	0.367	0.04	1.85	0.05	16.56	.2667

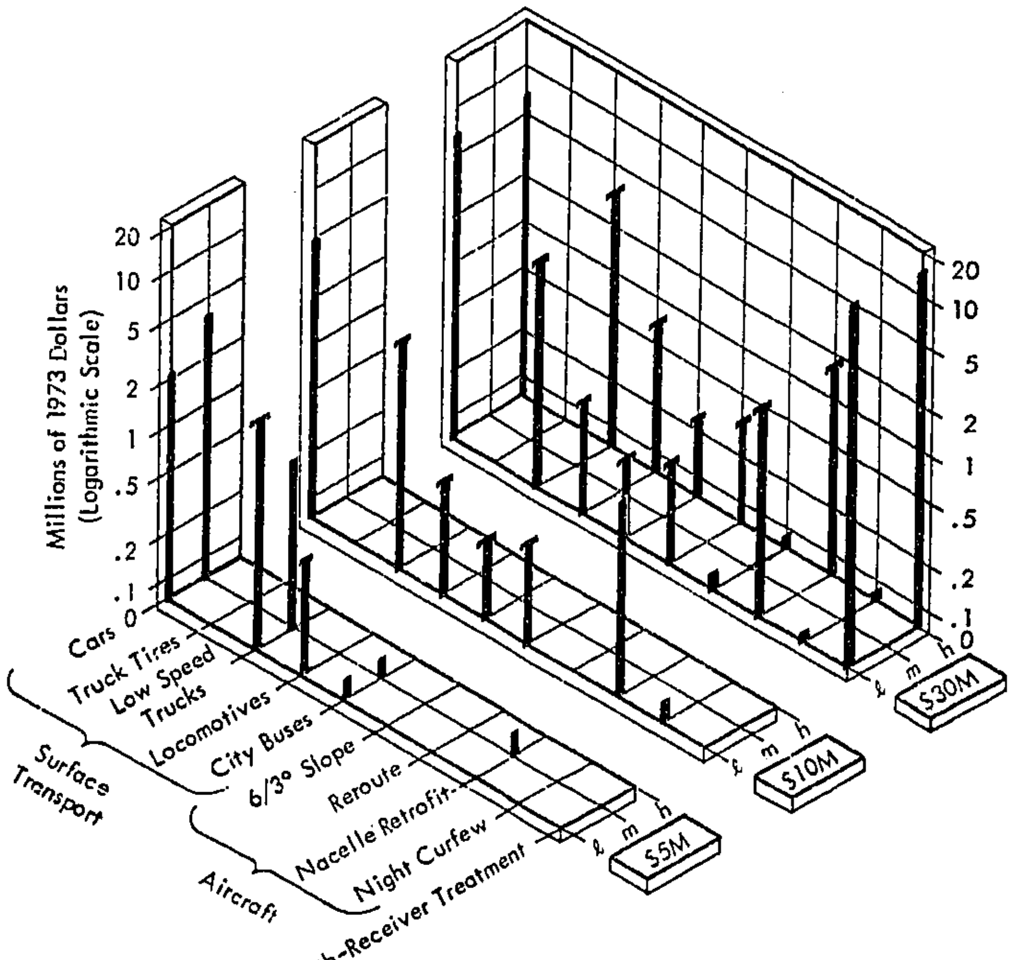

Figure 8.3-1. Optimum Noise Countermeasure Expenditure Scenarios, Northwest Third of Spokane, Linear Transfer Functions. ℓ = Low, m = Medium, h = High Countermeasure Cost Functions. A Bar at the Upper End of a Line Means Spending Limit Reached.

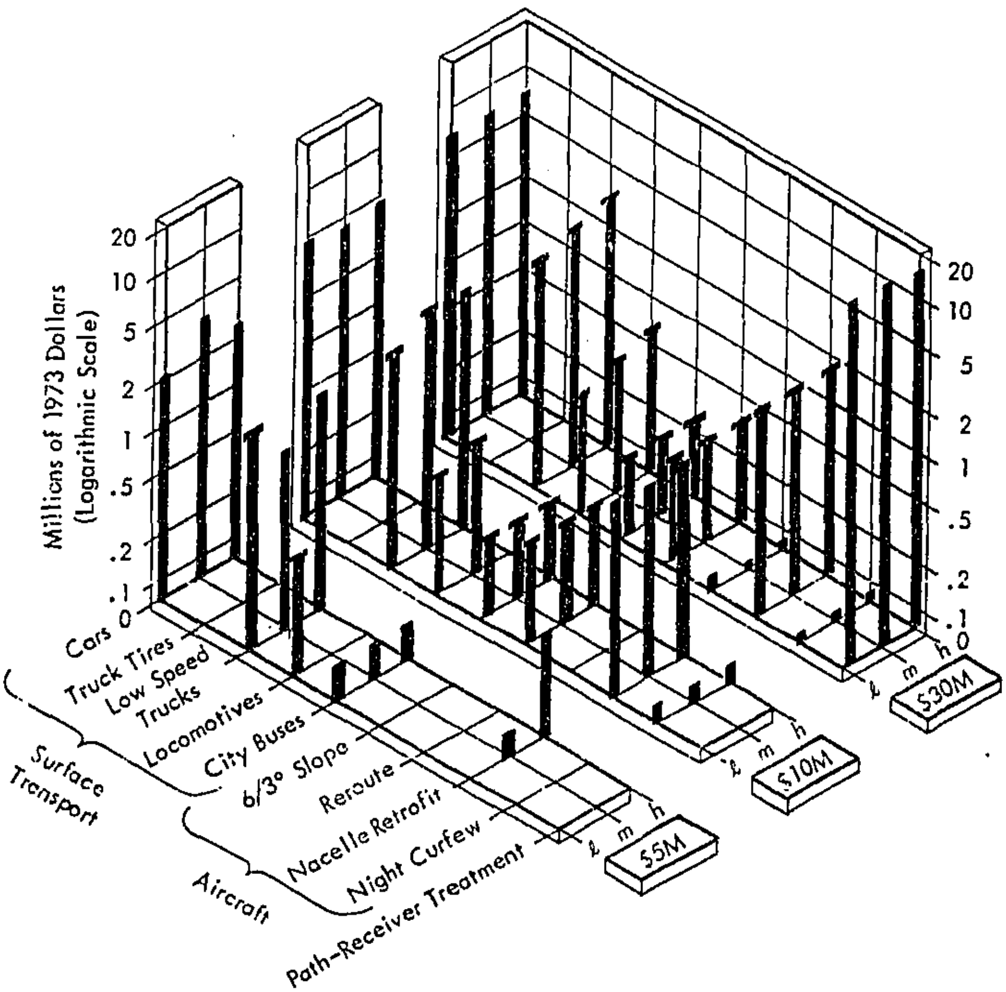

Figure 8.3-2. Optimum Noise Countermeasure Expenditure Scenarios, 24-Cell Representation of Northwest Third of Spokane, Linear Transfer Functions. See Figure 8.3-1 for Explanation of Symbols.

surface with many peaks and troughs (the "NII surface"). The lowest point of any trough is a minimum. The optimization procedure insures only that one of these minima is reached which is not necessarily the absolutely lowest point of the whole NII surface. Not knowing how many minima exist, it is at this point in time not possible to say with mathematical certainty that the best allocation of funds has been found in every case. However, having gained some working experience with the model, it is possible to state that the number of minima is probably small so that there is a good chance of finding the absolutely lowest point on the NII surface by varying the monies spent on countermeasures after a minimum has been found. If necessary, the optimization procedure is repeated to find a better minimum, i.e., a minimum with a lower NII value.

The cost-effective expenditure of funds will not necessarily be on the most dominant noise sources, but rather in those areas that give the most noise reduction for the money. One must be aware of the possibility that the most pervasive source of noise may also be the most expensive to treat and that such expenditures may yield limited benefits.

At the lowest level of total expenditure analyzed, $5 million, for the most part, only ground transportation source noise reduction is cost-effective. Aircraft noise reduction and path or receiver noise abatement treatment are not as cost-effective initially. The expenditures for noise reduction of automobiles (both low-speed and high-speed) and low-speed heavy trucks constitute the majority of effort, with the percentage allocations ranging from 88 to 95 percent for the low-to-high-cost ranges. It is found cost-effective to treat city buses to some extent. For the low range of countermeasure costs, locomotive noise reduction is incorporated to the maximum extent; however, other items are more cost-effective in the medium and high cost ranges. For all levels of total expenditure and all cost ranges, it never becomes cost-effective among the countermeasures considered to reduce high-speed heavy truck noise (primarily the tire component) by restricting the use of crossbar design tires on the drive axles.

At the second level of total expenditure analyzed, $10 million, one observes a broader distribution of funds, which now begin to encompass certain operational modifications for commercial aircraft. For all cost ranges, it is cost-effective to restrict night operations to some extent; implementation of a two-segment approach (6°/3° glide slope) into Spokane International Airport is found to be very effective in all cost ranges. Aircraft flight path rerouting is not effective at this level of expenditure. A sizable amount is expended on aircraft quiet nacelle retrofit. Path-receiver treatment is not effective at the $10 million level. Again as at the $5 million level, the majority of effort is directed toward autos, trucks, and buses, with autos and low-speed truck noise reductions accounting for 72 to 77 percent of the total low-to-high cost budgets. City buses are at their maximum possible level of treatment (a range of costs for such treatment was not available - hence, the same cost figures appear in the low, medium, and high cost ranges). Freight train locomotives receive maximum treatment for the low and medium cost ranges, but are not as cost-effective as other options for the high cost range.

At the highest level of expenditure analyzed, $30 million, nearly all source noise reduction countermeasures are incorporated to their maximum degree except for automobile noise reduction (and high-speed truck noise as previously mentioned) which remains at approximately the same allocation as in the $10 million case. Whereas before, auto and truck source modifications accounted for over 70 percent of the total budget, they have now dropped to 30 to 34 percent of the total. The expenditure allocations fall short of the maxima (for comparison, the spending limits on automobiles are 7, 22.75, and 38.5 million dollars for low, medium, and high cost ranges, respectively). In all cases (low, medium and high cost ranges), low-speed heavy truck reductions are incorporated to the maximum extent. The remainder of the funds are allocated to path-receiver treatments rather than further auto noise reduction. In fact, at this level of expenditure, these treatments account for from 59 to 55 percent of the total budget. It is interesting to note that a further analysis of which path-receiver modifications are deemed most cost-effective yields the result that dwelling sound insulation improvement in residential zones only is the single option deemed effective. Freeway or railroad barriers are not as effective for the Spokane analysis.

In concluding this discussion on the allocation of dollars on particular countermeasures, it is instructive to summarize the trends observed for the specific noise sources at increasing levels of expenditure as follows:

Automobiles: Most cost-effective to treat at the low and intermediate total budgets, however, become less cost-effective at the higher levels of noise reduction attainable once the initial reduction has been obtained.

Heavy Trucks: Low-speed truck noise reduction becomes increasingly cost-effective at all levels of expenditure up to reaching the maximum technically feasible noise reduction limit (for the 1978 time period). High-speed truck noise reduction achieved through restriction of crossbar tire tread design on the drive axles never becomes cost-effective.

Freight Train Locomotives: Become increasingly cost-effective at higher levels of expenditure until the maximum limits of noise reduction are reached.

City Buses in the Central Business District: Cost-effective to silence to some degree at the lower and to the maximum degree possible at the two higher levels of expenditure. This is significant in that buses as a distinct noise source are only analyzed in the Central Business District. However, 48 percent of the daytime population is assigned to the Central Business District.

Commercial Aircraft: Implementation of a two-segment approach procedure is the most cost-effective countermeasure, followed by quiet nacelle retrofit and night flight curfew. Aircraft flight track rerouting to avoid populated areas becomes only marginally cost-effective at the highest level of expenditure.

Path-Receiver Treatments: Only become cost-effective once all source reduction alternatives are exhausted (except for automobiles) at the highest level of expenditure. Very little additional benefit is achieved by increased spending for these options as indicated in Figure 8.2-2.

Table 8.3-4 and Figure 8.3-3 show the results of optimized noise countermeasure expenditure analyses for the 24-cell full city model representing the entire City of Spokane (see end of Section 8.2.3). The scenarios of optimum expenditures are essentially the same as the ones for the ordinary 24-cell subset of the northwest third of the City. This would indicate that it is not necessary to go through elaborate correction procedures in order to represent the entire City. The original carefully selected 24-cell sample seems to be adequate for carrying out the countermeasure analysis.

8.3.2 Effects of Variation of Endpoints and Slope of Transfer Functions

As discussed in Chapter 3 the upper and lower criterion levels for the exposure-response transfer functions were carefully selected from available data on human response. However, in some cases, this data is admittedly somewhat limited, thus creating some uncertainty as to the validity of these criterion levels. Also, average values of dwelling noise reduction were added to these limits to establish the outdoor levels. Thus, there indeed could be a significant tolerance in the upper and lower criterion levels. Hence, one should explore the sensitivity of the model to variations of the criterion levels. The left-most columns of Table 8.3-5 show what cases are considered. The symbols LC_{ℓ} and LC_{u} are the general criterion levels from Figure 2.4-1. For identifying the various cases, only the daytime criterion levels for residential areas are given. All other criterion levels are adjusted in an analogous way according to Table 3.2-6.

Table 8.3-5 and Figure 8.3-4 show the results of the optimizing analysis. Since the different transfer functions vary widely, so do the absolute values of the Noise Impact Index. One should therefore compare the last two columns (no expenditure and $10 million total expenditure) so that the relative change of NII with money spent becomes apparent. Thus, the greatest change in NII is observed for the 60 to 95 case: Here, people are assumed to register an adverse response only to the noisiest events. Since most of the money is spent to quiet the noisiest sources, a substantial reduction in NII should be expected here.

Table 8.3-4
Optimum Noise Countermeasure Scenarios,
24 Cells with Population Adjusted to Represent the Entire City of Spokane, Linear Transfer Functions
Underlined Numbers: Spending Limit Reached

Level of Total Expenditure in Millions of Dollars	Counter-measure Cost Functions	Cost Allocation per Countermeasure in Millions of Dollars										Noise Impact Index
		Automobile Noise Reduction – Low and High Speed	High Speed Heavy Truck Noise – Tires	Low Speed Heavy Truck Noise Reduction	Locomotive Noise Reduction – Freight and Passenger Trains	City Bus Noise Reduction in CBD	Commerical A/C: 6/3 Approach at Spokane International	Commerical A/C: Flight Path Rerouting	Commercial A/C: Quiet Nacelle Retrofit	Commerical A/C: Night Flight Restrictions at Spokane International	Path-Receiver Treatment: Barriers – Home Insulation – Relocation	
Baseline 1978												.2945
5	Low											
	Medium	3.8	0	0.97	0	0.14	0	0	0.116	0	0	.2402
	High											
10	Low											
	Medium	4.37	0	2.8	0.56	0.25	0.367	0	1.55	0.10	0	.2194
	High											
30	Low											
	Medium	6.85	0	2.8	0.56	0.25	0.367	0.04	1.85	0.05	17.21	.1995
	High											

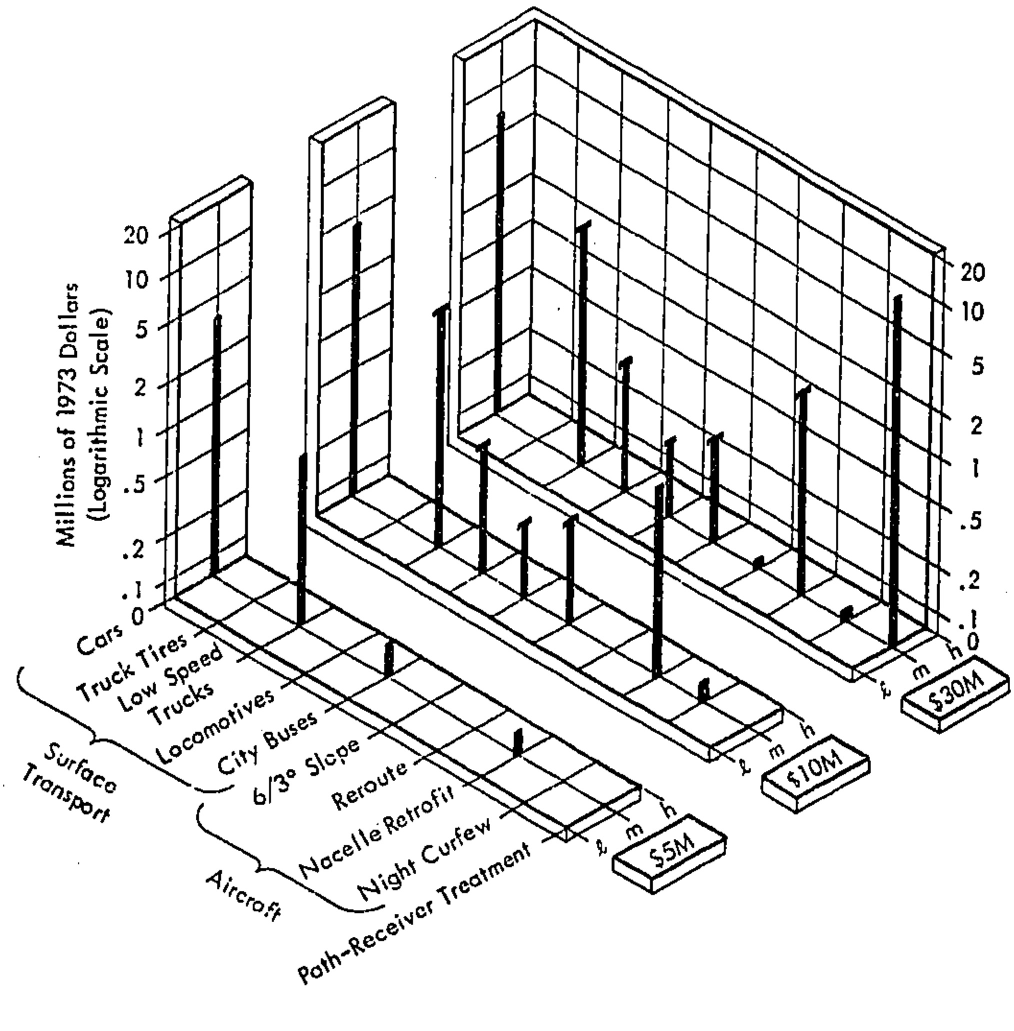

Figure 8.3-3. Optimum Noise Countermeasure Expenditure Scenarios, 24 Cells with Population Adjusted to Represent the Entire City of Spokane, Linear Transfer Functions. For Explanation of Symbols, See Figure 8.3-1.

Table 8.3-5

Optimum Noise Countermeasure Scenarios, 24-Cell Representation of Northwest Third of Spokane, Transfer Functions Linear with Varying Endpoints, Medium Cost Functions Only, $10 Million Total Expenditure Only. See Figure 3.4-1 and Table 4.2-6 for Illustration of LC_ℓ and LC_u. Underlined Numbers: Spending Limit Reached

Difference Between Upper And Lower Criterion Levels $LC_u - LC_\ell$ dB	Criterion Levels for Residential Areas, Day dB		Cost Allocation per Countermeasure in Millions of Dollars										Noise Impact Index	
	LC_ℓ	LC_u	Automobile Noise Reduction – Low and High Speed	High Speed Heavy Truck Noise – Tires	Low Speed Heavy Truck Noise Reduction	Locomotive Noise Reduction – Freight and Passenger Trains	City Bus Noise Reduction in CBD	Commerical A/C: 6/3 Approach at Spokane International	Commerical A/C: Flight Path Rerouting	Commerical A/C: Quiet Nacelle Retrofit	Commerical A/C: Night Flight Restrictions at Spokane International	Path-Receiver Treatment: Barriers – Home Insulation – Relocation	No Expenditure	$10M Total Expenditure
35	40	75	4.07	0	2.8	0.56	0.25	0.367	0	1.85	0.10	0	.6086	.5234
	50	85	4.37	0	2.8	0.56	0.25	0.367	0	1.55	0.10	0	.3440	.2801
	60	95	4.37	0	2.8	0.56	0.25	0.367	0	1.55	0.10	0	.0982	.0561
50	50	100	4.22	0	2.8	0.56	0.25	0.367	0	1.70	0.10	0	.2619	.2262
20	50	70	4.37	0	2.8	0.56	0.25	0.367	0	1.55	0.10	0	.5134	.4067

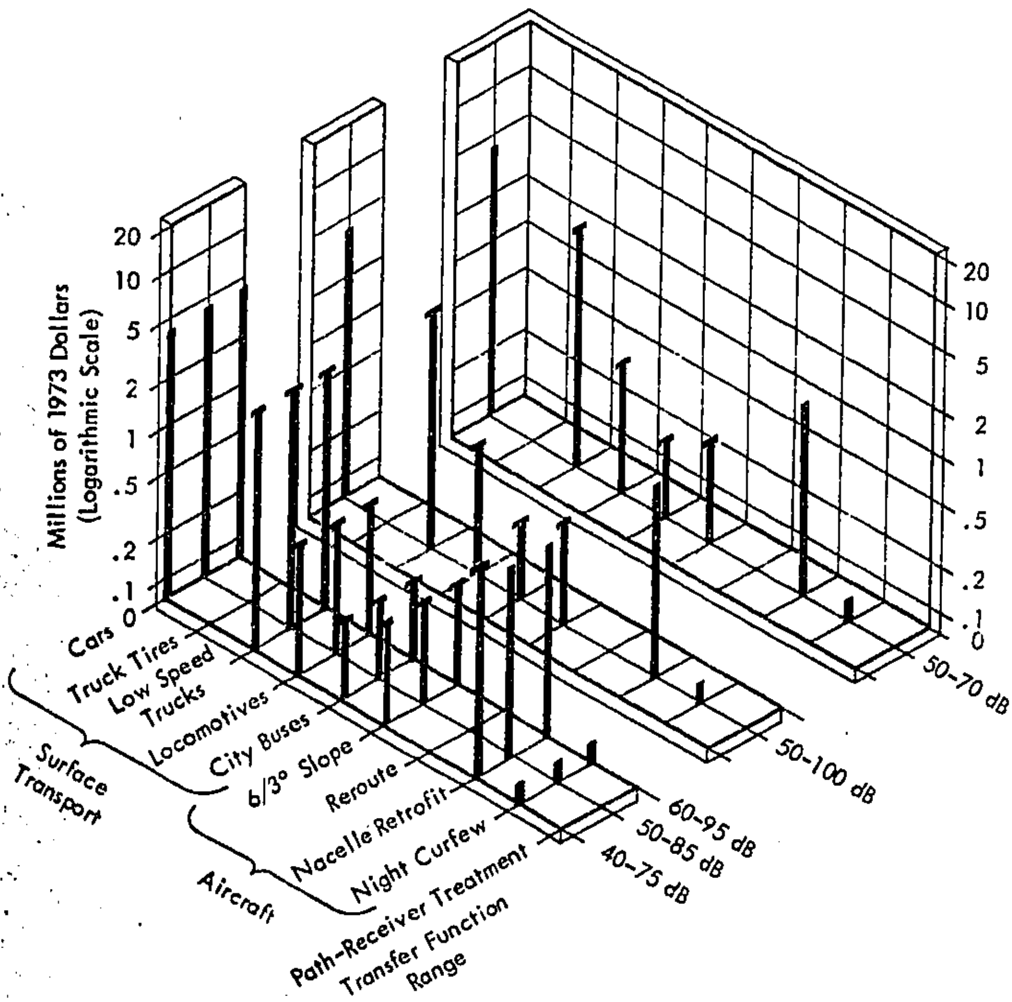

Figure 8.3-4. Optimum Noise Countermeasure Expenditure Scenarios, 24-Cell Representation of Northwest Third of Spokane, Transfer Functions Linear with Varying Endpoints, Medium Cost Functions Only, $10 Million Total Expenditure Only. Horizontal Lines on Top of Bars Signify Spending Limit Reached.

The optimized expenditure scenarios themselves look rather alike from case to case. This would indicate that the way funds are distributed over the noise countermeasures is generally insensitive to the transfer function endpoints. The only notable departure occurs for the 40 to 75 dB case where the countermeasure aircraft nacelle retrofit is exhausted to its spending limit.

Thus, we may conclude that while the absolute value of the NII is quite dependent upon the transfer function endpoints (as expected), the relative ranking in terms of where the expenditure is most cost-effective is relatively insensitive to shifts in the upper and lower criterion levels. It should be also pointed out that the noise levels from any of the unmodified sources never exceeded the upper criterion levels so that any noise reduction always resulted in a reduction of NII.

8.3.3 Nonlinear Transfer Functions

Just as it was necessary to investigate the effects of shifts in the upper and lower criterion levels, one should investigate the influence of the shape of the transfer function between these endpoints. The effects of changing the transfer function shape from a linear to a nonlinear curve is explored for two such shapes, a "parabola" and a "cosine" (s-shaped) transfer function. With reference to Figure 2.4-1, two nonlinear functions were evaluated with the part of the function between the lower (0 percent response) limit, LC_ℓ, and the upper (100 percent response) limit, LC_u, described by the following representations (see Figure 8.3-5):

$$\text{Parabola:} \quad \Phi(L) = \left(\frac{L - LC_\ell}{LC_u - LC_\ell}\right)^2 \qquad (8\text{-}1)$$

$$\text{Cosine:} \quad \Phi(L) = \frac{1}{2}\left[1 - \sqrt{\cos\left(\pi \frac{L - LC_\ell}{LC_u - LC_\ell}\right)}\right] \qquad (8\text{-}2)$$

where the root has the same sign as the cos (. . .) under the root.

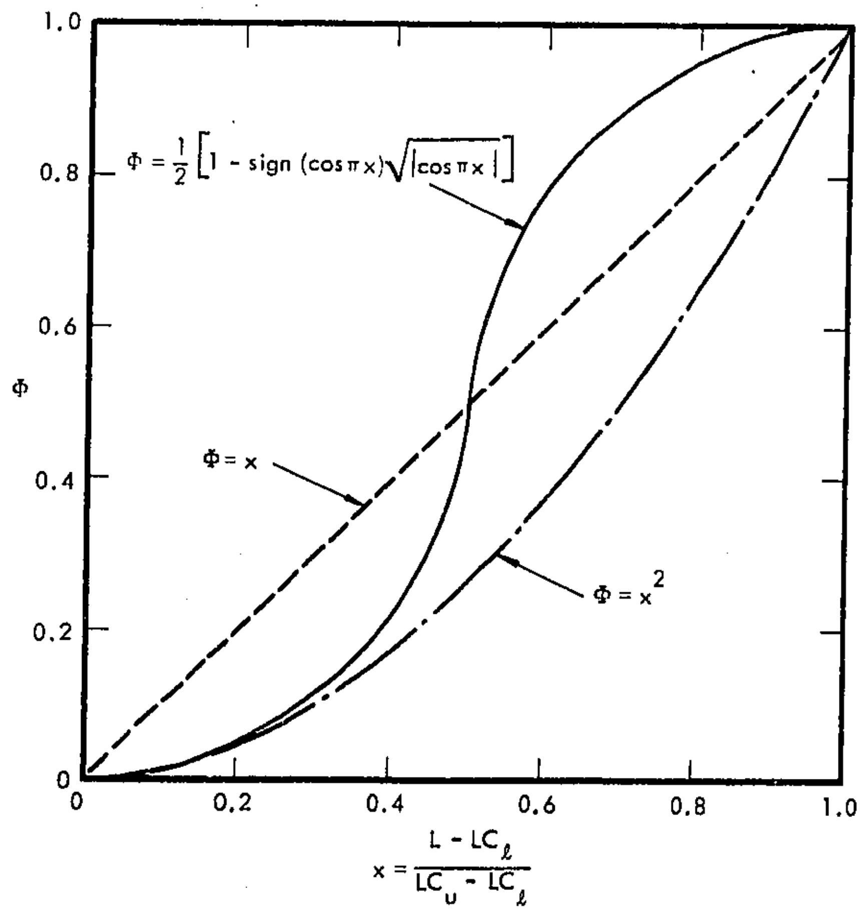

Figure 8.3-5. Nonlinear Transfer Functions, for LC_ℓ, LC_u, see Figure 2.4-1.

Table 8.3-6

Cases for Which an Optimum Noise Countermeasure Expenditure Scenario Has Been Found (Nonlinear Transfer Functions)

	Parabolic Transfer Function								
	$5M			$10M			$30M		
	ℓ	m	h	ℓ	m	h	ℓ	m	h
Northwest One-Third of City									
24-Cell One-Third City	x	x	x	x	x	x	x	x	x
24-Cell Full City Model									

	Cosine Transfer Function								
	$5M			$10M			$30M		
	ℓ	m	h	ℓ	m	h	ℓ	m	h
Northwest One-Third of City									
24-Cell One-Third City		x		x	x	x		x	
24-Cell Full City Model									

Table 8.3-6 shows for what cases optimized noise countermeasure expenditure scenarios are available. The results are given in Tables 8.3-7 and 8.3-8. They are almost identical to the ones of Table 8.3-3 which were obtained with linear transfer functions. The variations are so slight that it may be concluded that the expenditure scenarios are very insensitive to the shape of the transfer functions.

Table 8.3-7

Optimum Noise Countermeasure Scenarios,
24-Cell Representation of Northwest Third of Spokane, Parabolic Transfer Functions
Underlined Numbers: Spending Limit Reached

Level of Total Expenditure in Millions of Dollars	Countermeasure Cost Functions	Cost Allocation per Countermeasure in Millions of Dollars										Noise Impact Index
		Automobile Noise Reduction – Low and High Speed	High Speed Heavy Truck Noise – Tires	Low Speed Heavy Truck Noise Reduction	Locomotive Noise Reduction – Freight and Passenger Trains	City Bus Noise Reduction in CBD	Commerical A/C: 6/3 Approach at Spokane International	Commerical A/C: Flight Path Rerouting	Commercial A/C: Quiet Nacelle Retrofit	Commerical A/C: Night Flight Restrictions at Spokane International	Path-Receiver Treatment: Barriers – Home Insulation – Relocation	
Baseline 1978												.1425
5	Low	2.12	0	2.3	0.44	0.14	0	0	0	0	0	.1101
	Medium	3.8	0	0.97	0	0.14	0	0	.116	0	0	.1201
	High	2.4	0	2.25	0	0.14	0	0	0.35	0	0	.1250
10	Low	4.95	0	2.3	0.44	0.25	0.367	0	1.59	0.10	0	.0975
	Medium	4.37	0	2.8	0.56	0.25	0.367	0	1.55	0.10	0	.1040
	High	4.98	0	2.9	0	0.25	0.367	0	1.4	0.10	0	.1071
30	Low	6.85	0	2.3	0.44	0.25	0.367	0.07	1.85	0.05	17.82	.0915
	Medium	6.85	0	2.8	0.56	0.25	0.367	0.09	1.85	0.05	17.21	.0975
	High	6.85	0	3.35	0.68	0.25	0.367	0.04	1.85	0.05	16.56	.0987

Table 8.3-8
Optimum Noise Countermeasure Scenarios,
24-Cell Representation of Northwest Third of Spokane, Cosine Transfer Functions
Underlined Numbers: Spending Limit Reached

Level of Total Expenditure in Millions of Dollars	Counter-measure Cost Functions	Cost Allocation per Countermeasure in Millions of Dollars										Noise Impact Index
		Automobile Noise Reduction - Low and High Speed	High Speed Heavy Truck Noise - Tires	Low Speed Heavy Truck Noise Reduction	Locomotive Noise Reduction - Freight and Passenger Trains	City Bus Noise Reduction in CBD	Commerical A/C: 6/3 Approach at Spokane International	Commerical A/C: Flight Path Rerouting	Commercial A/C: Quiet Nacelle Retrofit	Commerical A/C: Night Flight Restrictions at Spokane International	Path-Receiver Treatment: Barriers - Home Insulation - Relocation	
Baseline 1978												.2221
5	Low											
	Medium	3.8	0	0.97	0	0.14	0	0	.116	0	0	.1926
	High											
10	Low	4.95	0	2.3	0.44	0.25	0.367	0	1.59	0.10	0	.1626
	Medium	4.37	0	2.8	0.56	0.25	0.367	0	1.55	0.10	0	.1698
	High	4.98	0	2.85	0	0.25	0.367	0	1.45	0.10	0	.1744
30	Low											
	Medium	6.85	0	2.8	0.56	0.25	0.367	0.04	1.85	0.05	17.21	.1614
	High											

8.3.4 Retrofit Labor Cost Sensitivity Substudy

All the results discussed so far have been obtained with motor vehicle noise reduction retrofit costs equal to the incremental manufacturing costs. In order to see how the picture changes when it is assumed that retrofit costs in the field are much higher than that, the retrofit hardware costs for automobiles, trucks, and buses have been tripled and new cost-versus-noise reduction functions computed. This is discussed in some detail in Section 7.4.2 (automobiles). In a similar way, the retrofit costs of trucks (Appendix G.2, Section 7.5) and buses (Section 7.6.2) have been adjusted. When the appropriate changes in the cost function computer file are made and a revised optimized set of countermeasure expenditures is sought, the results displayed in Table 8.3-9 and Figure 8.3-8 are obtained.

Tripling the motor vehicle retrofit hardware costs had the following impact on the results:

- Spending on low-speed trucks is halved.
- These funds are distributed on the countermeasures automobile quieting (cars) and aircraft nacelle retrofit.
- The aircraft countermeasures night curfew and rerouting exchange roles of being marginally and not at all cost-effective.

This tripling of retrofit costs had the greatest impact on trucks. Because the spending limit was reached on the aircraft nacelle retrofit countermeasure, the funds available from the truck countermeasure had to be spent on the next most cost-effective countermeasure which was automobiles despite the fact that retrofit hardware costs were tripled also in this category. Thus, we end up with the seemingly but not really paradoxical situation that more money (27 percent more) is spent on a countermeasure which has become more expensive. Note, however, that tripling the cost of retrofit for existing automobiles only increased the total cost of automobile source noise reduction by 35 percent because many more funds are spent on quieting new automobiles (the ratio is 4.75 to 1 for the medium cost range).

Table 8.3-9

Optimum Noise Countermeasure Scenarios, 24-Cell Representation of Northwest Third of Spokane, Linear Transfer Functions, $10 Million Total Expenditure, Medium Cost Functions. Comparison Between Simple and Triple Motor Vehicle Retrofit Hardware Costs. Underlined Numbers: Spending Limit Reached.

	Cost Allocation per Countermeasure in Millions of Dollars											Noise Impact Index
	Automobile Noise Reduction – Low and High Speed	High Speed Heavy Truck Noise – Tires	Low Speed Heavy Truck Noise Reduction	Locomotive Noise Reduction – Freight and Passenger Trains	City Bus Noise Reduction in CBD	Commerical A/C: 6/3 Approach at Spokane International	Commerical A/C: Flight Path Rerouting	Commerical A/C: Quiet Nacelle Retrofit	Commerical A/C: Night Flight Restrictions at Spokane International	Path-Receiver Treatment: Barriers – Home Insulation – Relocation	
Baseline 1978											0.3440
Simple Retrofit Hardware Costs*	4.37	0	2.80	<u>0.56</u>	<u>0.25</u>	<u>0.367</u>	0	1.55	0.1	0	0.2800
Triple Retrofit Hardware Costs	5.57	0	1.4	<u>0.56</u>	<u>0.25</u>	<u>0.367</u>	0.007	<u>1.85</u>	0	0	0.2875

*For this case, retrofit costs are assumed the same as incremental new product costs.

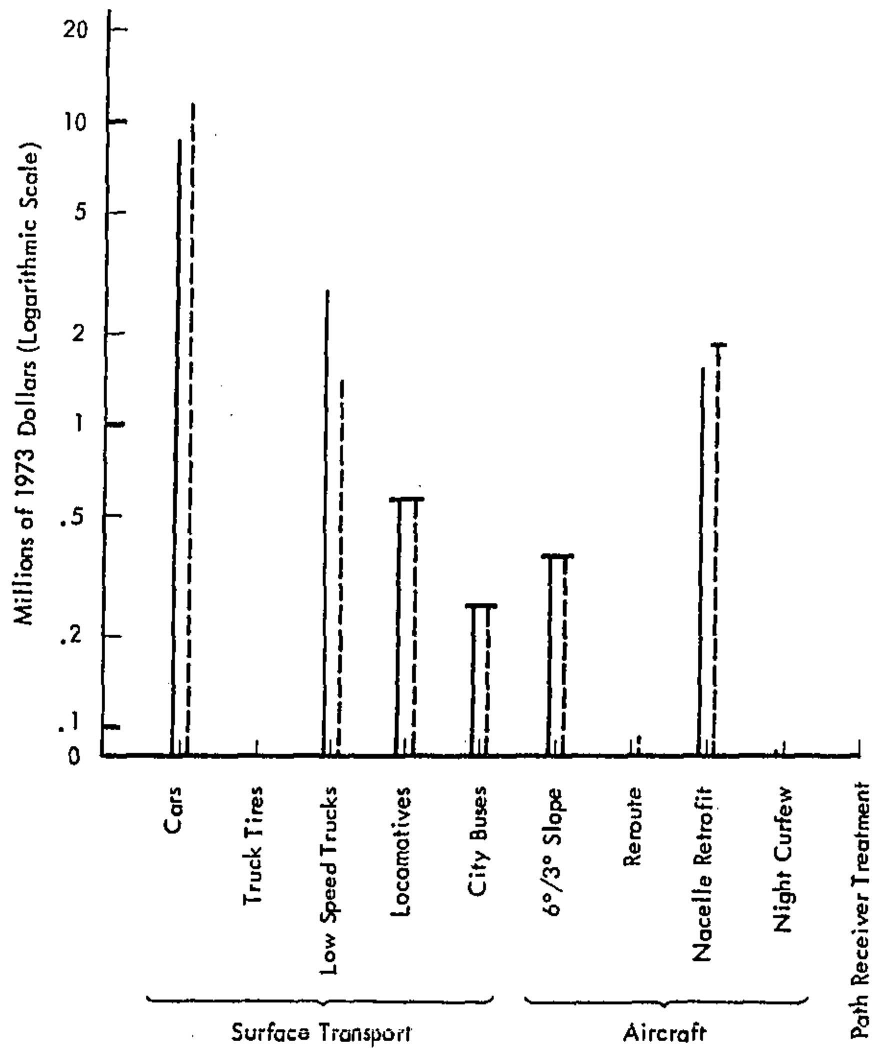

Figure 8.3-6. Optimum Noise Countermeasure Expenditure Scenarios, 24-Cell Representation of Northwest Third of Spokane, Linear Transfer Functions, $10 Million Total Expenditure, Medium Cost Functions. Solid Bars: Simple Motor Vehicle Retrofit Hardware Costs; Broken Bars: Triple These Costs. Horizontal Line on Top of Bars: Spending Limit Reached.

8.4 THREE-CELL STUDY OF NOISE COUNTERMEASURES, BASED ON L_{NP}

Chapter 2 discusses the possibility that the Noise Pollution Level L_{NP} may be a better predictor of human response to noise than the Energy Equivalent Level L_{eq}. But there exist major drawbacks which prevent L_{NP} from being used as the noise metric in the overall noise countermeasure cost-effectiveness calculation. In Chapter 3, transfer functions of noise level versus human response are developed only for L_{eq}. There is insufficient data available to permit the construction of transfer functions for L_{NP}. Thus, a very important link in the logical chain leading from the noise exposure to the people weighted Noise Impact Index is missing. Even if this link existed, Chapter 5 shows that the amount of data processing would increase tremendously over that in the L_{eq} analysis since a whole distribution function of noise levels would have to be defined for each source-receiver combination instead of just a single number.

The purpose of the study described in this section is to explore how the calculated outdoor noise levels change using as metrics L_{eq} and L_{NP}, and spending the same amounts of money on noise countermeasures in either case. Because of the large amount of data manipulation necessary, only three carefully selected cells located in the City of Spokane, Washington, are analyzed. Their locations are shown on Figure 8.4-1 together with the noise sources that predominantly influence these cells. A brief description of each cell follows:

Test cell number 1 is exposed by noise from one major arterial (Monroe) and from aircraft approaching on runway 21 and taking off from runway 03 of Spokane International Airport. The map also shows a flight track directly over test cell 1 associated with military training flights originating at Fairchild Air Force Base. These are not considered in this study due to insufficient data available to construct the statistical distribution functions of noise levels.

Test cell number 2 is located in the Central Business District. It is exposed by noise from city transit buses and other general traffic on two major arterials (Wall and Riverside).

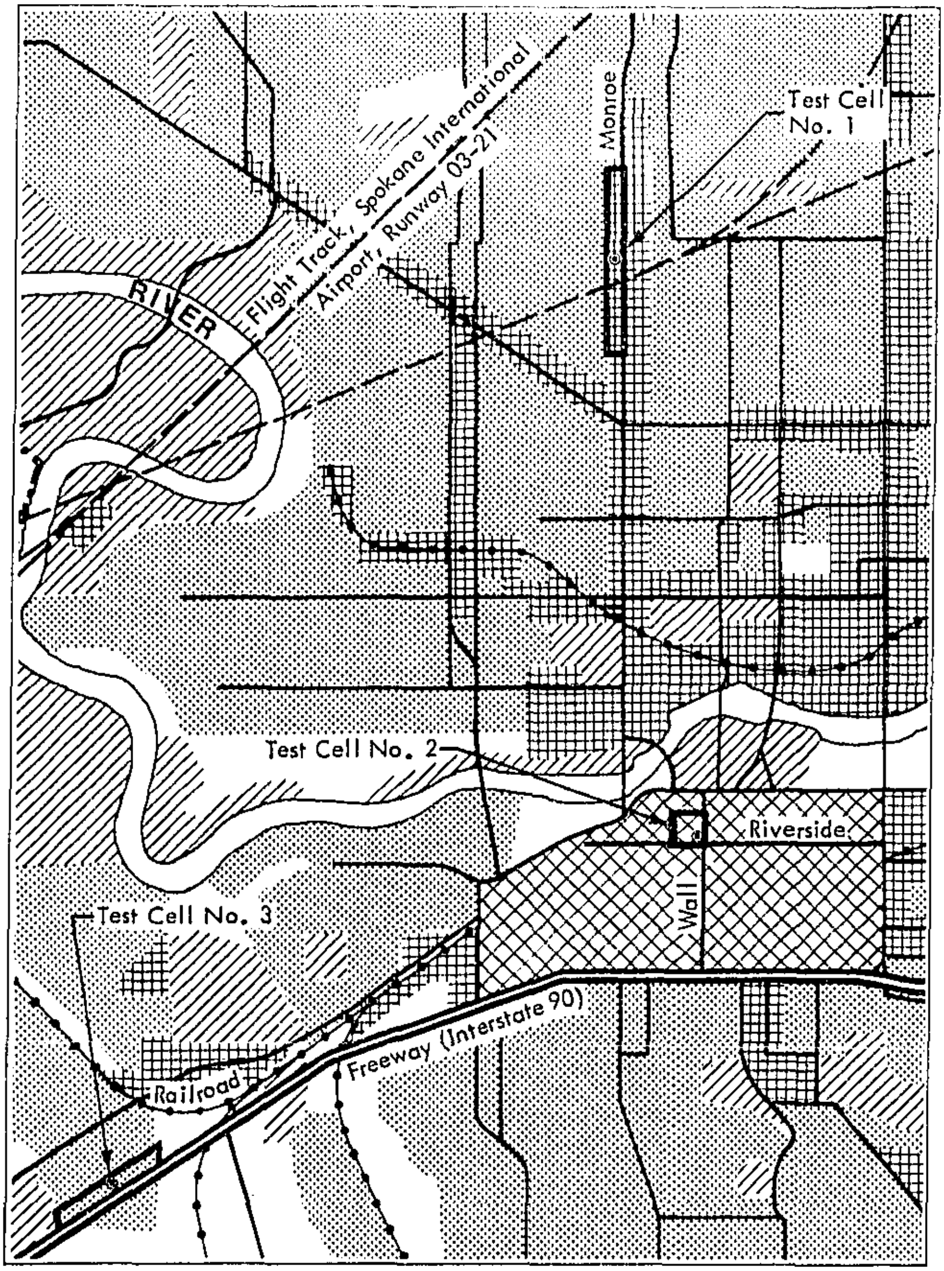

Figure 8.4-1. Partial Map of City of Spokane, Washington, Showing Locations of Test Cells Used in the L_{NP} Study.

Test cell number 3 is exposed to noise from a freeway (Interstate 90) and railway lines.

As can be seen, the test cells are chosen such that the change of noise metrics due to countermeasures applied to each major noise source can be observed. Path-receiver treatments (like for instance barriers) are not considered.

8.4.1 Test Cell Data

The general method used for obtaining cumulative distributions for noise sources is described in Chapter 5 of this report. The specific data used in each test cell is presented below. It is taken from statistics compiled for the L_{eq}-analysis (Appendix B) and is applicable for daytime only.

- Test Cell Number 1

  Monroe Street is a four-lane arterial. There are a total of 892 cars per hour and 47 trucks per hour on this arterial. Tables 8.4-1, 8.4-2, and 8.4-3 show the generalized lane distributions and speed distributions that have been assumed throughout this analysis. The average speed of the cars is 27.5 mph and there are 32.44 cars per mile. The average speed of the trucks is 20.5 mph and there are 2.29 trucks per mile. Equations (4-1) and (4-2) are used to obtain motor vehicle reference noise levels at 50 feet (with the small correction to account for noise regulation differences between California and Washington; see Chapter 4). The populace of test cell 1 is assumed to be at an exposure distance of 50 feet from Monroe Street (see Appendix C, Section C.3, for an explanation of the term "exposure distance").

  Test cell 1 is located 2000 feet (slant range) from the flight path associated with runway 03-21 of Spokane International Airport. Aircraft operations are divided into four classes. The pertinent data is shown in Table 8.4-4.

Table 8.4-1

Generalized Lane Distribution of Road Traffic by Vehicle Class[S16]

Highway Lane Configuration		Percent by Class in Each Lane*			
		1	2	3	4
8-Lane	Cars Trucks	15 60	25 35	30 04	30 01
6-Lane	Cars Trucks	25 66	40 33	35 01	
4-Lane	Cars Trucks	50 90	50 10		
2-Lane	Cars Trucks	100 100			

Table 8.4-2

Generalized Speed of Road Traffic by Vehicle Class

Low Speed Arterials

Highway Lane Configuration		mph in Each Lane*	
		1	2
4-Lane	Cars Trucks	25 20	30 30
2-Lane	Cars Trucks	30 25	

Table 8.4-3

Generalized Speed of Road Traffic by Vehicle Class

High Speed Arterials and Freeways

Highway Lane Configuration		mph in Each Lane*		
		1	2	3
6-Lane	Cars Trucks	55 50	60 55	65 60

*Opposite lane symmetry assumed.

Table 8.4-4

Statistics of Commercial Aircraft Operations, Runway 03-21, Spokane International Airport

Aircraft Class (Jets Only)	Maximum A-Weighted SPL at 2000 Feet	Number of Flights Per Day	Velocity ft/sec
2-Engine (DC-9)	76	12.12	290
3-Engine (727)	76	22.5	290
4-Engine (707)	81	3.03	290
Wide Body (DC-10)	71	3.03	290

- Test Cell Number 2

  On Wall Street, a two-lane arterial, there are 364 cars per hour and 23 trucks per hour. The average speed of the cars is 30 mph and there are 12.13 cars per mile. The average speed of the trucks is 25 mph and there are 0.92 trucks per mile. The populace exposure distance is assumed to be 50 feet from Wall Street.

  On Riverside Avenue, a four-lane arterial, there are 695 cars per hour, 44 trucks per hour, and 19.53 buses per hour. The average speed of the cars is 27.5 mph and there are 25.27 cars per mile. The average speed of the trucks is 20.5 mph and there are 2.146 trucks per mile. The average speed of the buses is 25 mph and there are 0.78 buses per mile. The populace exposure distance is assumed to be 50 feet from Riverside Avenue.

- Test Cell Number 3

  On Interstate 90, a six-lane freeway, there are 1473 cars per hour and 146 trucks per hour. The average speed of the cars is 60.5 mph and there are 24.35 cars per mile. The average speed of the trucks is 51.75 and there are 2.82 trucks per mile. The populace exposure distance is assumed to be 50 feet from Interstate 90.

There are 1.25 trains per hour passing by this test cell. The average length of the trains is taken to be 4500 feet and the average speed 25 mph. The railroad tracks are at a distance of 1100 feet from the populace of the test cell.

8.4.2 Analysis

For each cell the cumulative distribution of noise levels is calculated for each source as detailed in Chapter 5 using the information listed above. Figure 8.4-2 shows typical distributions for some of the source-receiver combinations. For each test cell, the individual source distributions are combined by the method given in Section 5.2. Finally, L_{NP} can be calculated using Eq. (5-4). L_{eq} does not have to be calculated separately as it is an intermediate result in the L_{NP} calculation. In this way, the lines labeled "baseline" of Table 8.4-5 are obtained.

In order to explore how the picture changes when funds are expended on noise countermeasures, the following procedure is used. The maximum allowable amounts are spent on each source except on automobiles following the medium cost functions derived in Chapter 7. The relationships between 1973 dollars and effected noise reductions are:

$10 million, automobiles ——→ { 2 dB, low speed; 1 dB, high speed tire noise }

$2.825 million, trucks ——→ 8 dB, low speed

$0.135 million, city transit buses ——→ 6 dB

$0.561 million, locomotives ——→ 5 dB

No money is spent on airplanes and high speed truck tire noise since the quieting of these sources has proven not be be cost-effective in the daytime L_{eq} analysis (Section 8.3) (the present L_{NP} study considers daytime only).

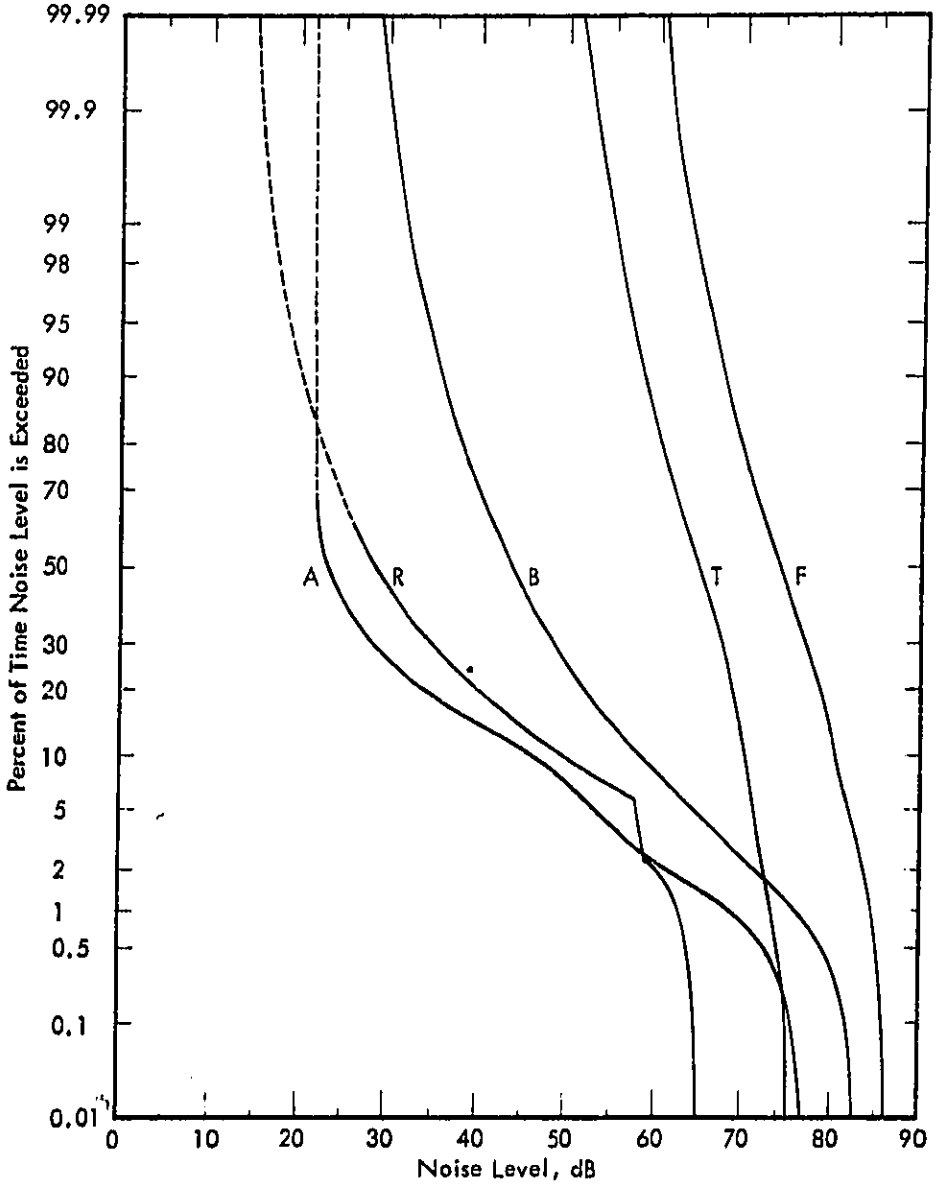

Figure 8.4-2. Typical Distribution Functions of Noise Levels from Different Sources, Spokane, Washington. A: Aircraft Traffic in Test Cell 1, R: Railroad Noise in Test Cell 3, B: Buses on Riverside Avenue in Test Cell 2, T: Motor Vehicles on Monroe Street in Test Cell 1, F: Motor Vehicles on Freeway (Interstate 90) in Test Cell 3. Dashed Line: Levels so Low That Not Used in Analysis.

Table 8.4-5

Results of L_{NP} Analysis for the Three Test Cells

Indices 0 and i Refer to Line Number Given in Left Most Column

i	(a) Test Cell 1	L_{eq_i} dB	L_{NP_i} dB	$\frac{L_{eq_0} - L_{eq_i}}{\$M\ Spent}$	$\frac{L_{NP_0} - L_{NP_i}}{\$M\ Spent}$
0	Baseline (No Money Spent)	67.0	78.4	0	0
1	Spend $2.825M on Trucks	65.5	76.2	.527	.776
2	In Addition, Spend $10M on Automobiles	63.9	74.7	.245	.288

i	(b) Test Cell 2	L_{eq_i} dB	L_{NP_i} dB	$\frac{L_{eq_0} - L_{eq_i}}{\$M\ Spent}$	$\frac{L_{NP_0} - L_{NP_i}}{\$M\ Spent}$
0	Baseline (No Money Spent)	69.1	80.2	0	0
1	Spend $0.135M on City Transit Buses	68.4	79.2	4.637	7.385
2	In Addition, Spend $2.825M on Trucks	67.4	77.6	.570	.877
3	In Addition, Spend $10M on Automobiles	64.8	74.5	.331	.438

i	(c) Test Cell 3	L_{eq_i} dB	L_{NP_i} dB	$\frac{L_{eq_0} - L_{eq_i}}{\$M\ Spent}$	$\frac{L_{NP_0} - L_{NP_i}}{\$M\ Spent}$
0	Baseline (No Money Spent)	76.7	89.3	0	0
1	Spend $2.825M on Trucks	76.2	88.4	.191	.305
2	In Addition, Spend $10M on Automobiles	75.564	88.207	.088	.082
3	In Addition, Spend $.561M on Locomotives	75.562	88.225	.085	.077

In Reference S14 it was found that the distribution of noise levels from heavy trucks hardly changes its shape when source noise reduction is applied, but simply shifts to lower noise levels. For the present analysis it is assumed that this holds true for all above sources. Thus, for example, the noise level distribution for city buses is shifted 6 dB down when $0.135 million is spent to quiet the buses.

The above countermeasures are applied in a sequence gleaned from the L_{eq} analysis, i.e., money is spent first on the countermeasure that was most cost-effective there. The distribution with their L_{NP}'s are recalculated. The results are presented in Table 8.4-5.

8.4.3 Discussion

The last two columns of Table 8.4-5 give an indication of how much noise reduction is achieved for the money that is spent. Of course, these figures are applicable only to the particular test cell under consideration. Also, it must be remembered that it is not attempted here to relate noise levels to human response. The dimension of those noise reduction to expenditure ratios is decibels per million dollars. One would like to have this ratio as large as possible. Thus, it can be seen that city transit bus noise reduction would be very effective for test cell 2, whereas test cell 3 does not seem to profit a great deal from any expenditure.

The ratios based on L_{NP} show in most cases a similar trend to those based on L_{eq}, except in test cell 3, cases 2 and 3, where the L_{NP}-ratios are smaller than the L_{eq}-ratios. In all other cases it is the other way around.

The essential difference between L_{eq} and L_{NP} is that any money spent on any noise countermeasure will decrease L_{eq}. This is not necessarily so with L_{NP}. Looking at Eq. (2-7), one observes that the variability factor $K\sigma$ may increase more than L_{eq} decreases if money is spent unwisely on an ineffective noise source. Take, for example, a residential area close to an industrial complex which provides a more or less steady background noise. Lowering the latter may substantially increase the standard deviation σ if the statistics of noise peaks (for instance from motor vehicles) remain the same.

In the cases examined here money is always spent on the most cost-effective source first. Both L_{eq} and L_{NP} decrease every time a countermeasure is applied. It would appear from this cursory look that the scenarios of the distribution of funds on noise countermeasures would not be substantially different whether the underlying noise metric is L_{eq} or L_{NP}. However, the reverse of trend in ratios of the last two cases in Table 8.4-5 indicates that there probably exist situations where an L_{NP} analysis would result in a different allocation of funds from that resulting from an L_{eq} analysis. At this point, it is unclear what the extent of this difference may be.

To summarize the latter part of this chapter, the general trends of optimum scenarios of countermeasure expenditures, presented earlier in Section 8.3, do not seem to be sensitive to either the endpoints or slope of the human response transfer functions utilized. However, some sensitivity in the results to the particular noise metric is suggested by a brief comparison between a limited set of scenarios using both the L_{NP} and L_{eq} noise metrics.

Finally, it should again be pointed out that this study was necessarily limited in the scope of noise sources and countermeasures considered. In general, fixed external noise sources, noise from faulty equipment or poor driving habits (brake squealing, tire screeching, etc.) and indoor self-generated noise sources were not considered. Costs of enforcement and the community noise reduction effectiveness of field enforcement with operational restrictions were not included. These limitations must be carefully considered when attempting to draw conclusions from this study with policy-making implications on community noise reduction.

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APPENDIX A

MODEL CITY SELECTION

The Wyle community noise model with its optimization process was applied to a "real" city. The choice of an actual U.S. community over a hypothetical model is an important one and was made for two main reasons. The first being that, whatever the formulation of a hypothetical city, the doubt always would persist as to whether results gained from that city apply to any given physical community. The second reason is that if, during the optimization analysis, it is decided that additional detail is required for the model, it may not be available from the statistics used to construct the hypothetical city. On the other hand, detailed information always exists for a real community. It has only to be collected.

After deciding to analyze a real city, it was necessary to select a "typical" or "average" community. The distinction between typical and average may be slight, but it is significant for this program with respect to the properties of the city selected for analysis. As can be seen from Table A-1 or Figure A-1, the size and population densities of U.S. cities tend to cluster loosely into two groups; medium to small cities with population densities generally less than 6000 people per square mile and large cities with population densities greater than 6000 people per square mile. Our selected city fell within the groupings indicated for medium and small cities, whereas the statistically "average" U.S. city falls somewhere between these two groups in an area where there are few actual candidate cities.

The following outlines the selection criteria used to select the model city which was to lie close to the average U.S. city — somewhere between the "large" and "small" city clusters indicated in Table A-1.

Table A-1

Approximate Percent Distribution of Population in Urban Places with Population over 2500 as a Function of Population Density

Population	Density Per Square Mile									Total %
	< 1000	1-2000	2-3000	3-4000	4-6000	6-10,000	10-15,000	15-20,000	> 20,000	
> 1 Million				0.9(3)		2.0(4)	1.1(5)	3.9(6)	5.7(7)	13.6
500,000 - 1 Million		0.5	1.5	2.6	1.0	2.6	1.5	0.5	-	10.2
250,000 - 500,000		0.8	0.8	2.0	1.8	1.5	0.3	0.5	-	7.7
100,000 - 250,000		0.8	2.8	2.2	3.4	1.5	0.6	0.2	-	11.5
50,000 - 100,000	0.2	1.1	2.7	1.9	2.9	2.7	0.6	0.2	0.1	12.4
25,000 - 50,000	0.6	2.3	3.0	2.3	2.7	1.8	0.5	0.1	0.1	13.4
10,000 - 50,000	2.2	3.1	3.8	2.4	2.5	1.5	0.3	0.1	<0.1	15.9
5,000 - 10,000	1.6	2.7	2.3	1.1	1.0	0.6	0.1	<0.1	<0.1	9.4
2,500 - 5000	1.6	2.0	1.3	0.5	0.3	0.1	<0.1	<0.1	<0.1	5.9
Total	6.2	13.3	18.2	15.9	15.6	14.3	5.1	5.5	5.9	100%(2)

(1) Derived from Table 31 in "Number of Inhabitants, United States Summary (PC(1)-A1)," Bureau of the Census, December 1971 (1970 Census Data).

(2) 100% corresponds to the total population of about 133,500,000 (or about 66% of the U.S. population) who live in 6,435 urban places with population greater than 2,500.
The remaining population consists of about 15,900,000 in other smaller urban areas and about 53,800,000 in rural areas.

(3) Houston

(4) Los Angeles

(5) Detroit

(6) Chicago, Philadelphia

(7) New York

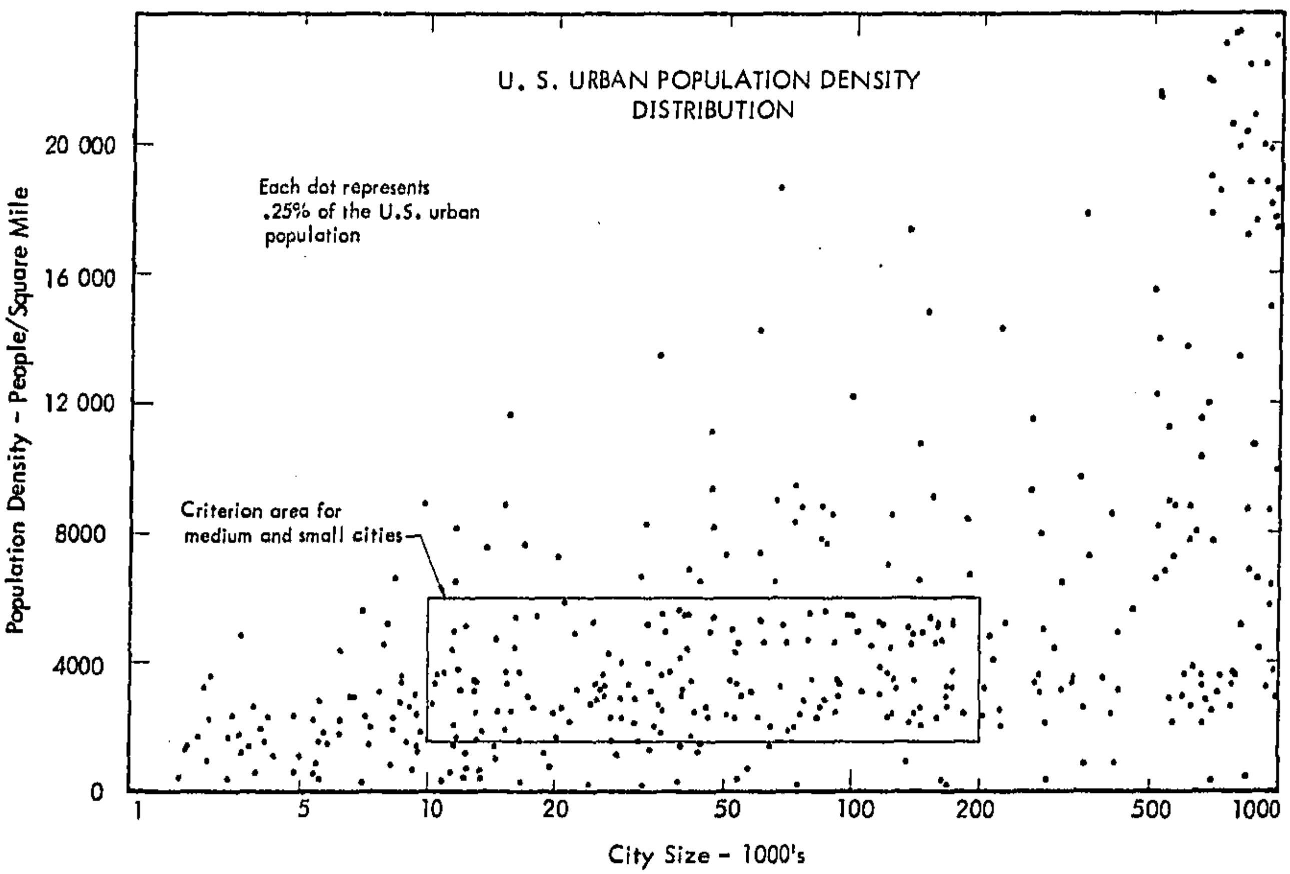

Figure A-1. Population Density Versus U.S. City Size

A.1 Initial Model City Candidates

Based on the general demographic patterns illustrated in Table A-1 and Figure A-1, and in the program objectives, the following four criteria were applied to all U.S. cities to obtain an initial list of candidate sites.

1. The city must be a self-contained urban area surrounded by rural land.
2. The city must have a population between 10 and 200 thousand people.
3. Population density must be between 1500 and 6000 persons per square mile.
4. There must be an airport with scheduled jet traffic within 10 miles of the city center.

The first criterion was chosen to weed out those cities and suburbs that depend economically and otherwise on nearby larger communities. For such cities, county economic statistics would not necessarily be meaningful and population distributions would be different than for cities that are self-sufficient. The population and population density criteria were purposely chosen to include a large number of cities. Since the placement of city boundaries vary widely and the boundaries do not necessarily follow the limits of urban population, it means that the published city densities are only a loose measure of actual spot population densities. The airport proximity criterion was included simply to insure that the community was exposed to some extent to noise from air carrier aircraft.

Application of these criteria to 1970 census data on all of the major U.S. cities produced the set of 133 cities found in Table A-2. Additional criteria were then applied to these candidate cities to narrow the possible choices.

Table A-2

Model City Candidates

State	Candidate City	City Population 1000's	Area Sq.Mi.	Population Density /Sq.Mi.	County	County Population 1000's	Airport Location Miles	Community Indicators (on a Per Capita Basis): Households with Autos Percent	Value Added by Manufacturing $/Capita-Year	3 Month Payroll Motor Freight & Warehousing $/Capita	Annual Gas Sales $/Capita
Alabama	Montgomery	133	46	2875	Montgomery	168	7 SW	78.1	484	8.52	120
	Sheffield	13	7	1930	Colbert	50	6 E	86.2	2920*	7.03	82*
	Tuscaloosa	66	27	2400	Tuscaloosa	116	5 NW	80.2	1021	4.73	111
Alaska	Anchorage	48	16	2965	Anchorage	125	7 SW	93.5	126	7.46	255
	Fairbanks	15	5	3210	Fairbanks	46	4 SW	89.9	52*	–	87*
Arkansas	Hot Springs	36	23	1520	Garland	54	3 SW	72.2	436	3.69	149
	Texarkana	22	8	2645	Miller-Ark.	33	4 NE	76.9	436	13.44	267
					Bowie-Tex.	68					
California	Bakersfield	69	26	2685	Kern	330	3 NW	86.4	517	7.50	309
	Fresno	166	42	3970	Fresno	413	7 NE	85.1	422	12.99	185
	Salinas	59	13	4430	Monterey	250	3 E	89.8	837	5.91	38
	Santa Barbara	70	21	3345	Santa Barbara	264	8 W	82.4	417	4.55	200
	Stockton	108	25	3600	San Joaquin	290	5 SE	79.7	1074	16.42	196
Colorado	Colo. Springs	135	61	2220	El Paso	236	7 E	81.2	402	4.14	112
	Grand Junction	20	6	3540	Mesa	54	4 NE	88	1528*	11.45	101*
	Pueblo City	97	23	4330	Pueblo	118	6 E	85.8	992*	6.16	123
Florida	Bradenton	21	12	1800	Manatee	97	8 S	86.9	442*	1.01	107
	Daytona Beach	45	23	1990	Volusia	169	1 W	96.7	967	4.01	192
	Fort Myers	27	12	1720	Lee	105	4 S	81.1	281	4.46	274
	Gainesville	64	26	2470	Alachua	105	7 NE	87.7	272	2.08	153
	Melbourne	40	26	1555	Brevard	230	1 NW	91.3	1351*	–	85
	Orlando	99	28	3600	Orange	344	10 SE	78.9	524	18.20	211
	Panama	32	14	2325	Bay	75	4 NW	82.6	493	7.30	238
	Pensacola	59	24	2480	Escambia	205	3 NE	78.1	698	6.72	171
	Sarasota	40	14	2875	Sarasota	120	4 NW	82.2	428	5.71	210
	Tallahassee	72	26	2755	Leon	103	7 SW	86.6	135	7.02	130
	Titusville	31	15	2010	Brevard	230	3 S	93.1	58	–	133
	W. Palm Beach	57	38	1500	Palm Beach	349	4 SW	79.8	398	4.77	191
Georgia	Albany	73	29	2470	Dougherty	90	4 SW	78.3	759	11.91	109
	Augusta	60	15	3940	Richmond	162	8 S	64.0	1335	12.53	170
	Macon	122	49	2500	Bibb	143	8 S	75.9	1242	12.08	173
Idaho	Boise	75	23	3200	Ada	112	5 S	90.2	331	11.57	151
	Idaho Falls	36	9	3810	Bonneville	51	2 NW	91.8	611	7.85	152
	Lewiston	26	15	1725	Nez Perce	30	1 S	87.6	2253*	23.77	134
	Pocatello	40	14	2920	Bannock	52	8 NW	90.3	275	27.43	193
	Twin Falls	22	7	3370	Twin Falls	42	5 S	90.1*	574*	18.81	128*

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Table A-2 (Continued)

State	Candidate City	City Population 1000's	Area Sq. Mi.	Population Density /Sq. Mi.	County	County Population 1000's	Airport Location Miles	Community Indicators (on a Per Capita Basis): Households with Autos Percent	Value Added by Manufacturing $/Capita-Year	3 Month Payroll Motor Freight & Warehousing $/Capita	Annual Gas Sales $/Capita
Illinois	Decatur	90	31	2955	Macon	125	4 E	83.4	3903	18.13	146
	Peoria	127	37	3395	Peoria	195	5 SW	82.1	1628	15.21	145
	Springfield	92	25	3640	Sangamon	161	3 NW	81.1	1135	6.22	215
Indiana	Anderson	71	37	1910	Madison	138	3 N	86.8	5931	4.87	124
	Evansville	139	36	3855	Vanderburgh	169	5 NE	82.3	2161	25.71	170
	Ft. Wayne	178	52	3450	Allen	280	9 SW	85.3	2074	22.97	157
	Muncie	69	13	5400	Delaware	129	3 N	82.9	3358	12.03	167
	New Castle	21	5	4080	Henry	53	3 N	88.9*	1657*	–	127*
	South Bend	126	29	4300	St. Joseph	245	4 W	83.5	2219	20.64	132
Iowa	Cedar Rapids	110	51	2180	Linn	163	8 S	86.8	3810	11.10	141
	Iowa City	47	21	2220	Johnson	72	8 S	85.4	2028	5.88	140
	Sioux City	86	52	1650	Woodbury	103	6 SE	83.0	1074	19.94	140
	Waterloo	76	46	1640	Black Hawk	133	6 NW	85.9	3746	7.39	143
Kentucky	Lexington	108	23	4700	Fayette	174	4 SW	79.9	1046	14.64	170
	Owensboro	50	9	5920	Daviess	79	4 SW	82.6	1518	7.92	102
	Paducah	32	12	2660	McCracken	58	9 N	77.5	–	13.40	190
Louisiana	Baton Rouge	166	40	4100	East & West Baton Rouge	302	8 N	85.7	1735	6.71	141
	Lafayette	69	20	3450	Lafayette	110	1 E	86.3	213	6.61	148
	Monroe	56	22	2540	Ouachita	115	6 E	76.0	407	7.91	127
	Shreveport	182	57	3200	Caddo	230	5 SW	80.7	624	14.37	104*
Maine	Portland	65	21	3015	Cumberland	193	2 W	68.5	1118	22.69	155
Massachusetts	Worcester	177	37	4720	Worcester	638	5 W	73.8	2438	9.76	113
Michigan	Flint	193	33	5890	Genesee	444	4 SW	84.7	–	10.55	137
	Lansing	131	33	3940	Ingham	261	4 NW	87.2	4871	10.60	129*
	Muskegon	45	13	3435	Muskegon	157	5 S	82.2	4598	14.74	166
	Saginaw	92	17	5310	Saginaw	220	10 NW	82.0	3085	6.70	135
	Traverse City	18	8	2315	Grand Traverse	39	2 SE	91.5*	815*	6.71	147*
Minnesota	Rochester	54	13	4010	Olmsted	84	10 S	85.8	1446	10.13	150
Mississippi	Columbus	26	8	3110	Lowndes	50	9 W	71.2	1381	3.57	113
	Greenville	40	8	4950	Washington	71	6 NE	70.1	833	8.91	80
	Gulfport	41	26	1580	Harrison	135	4 NE	85.9	698	5.46	128
	Jackson	154	50	3070	Hinds	215	10 E	82.1	872	14.98	149
	Meridian	45	25	1775	Lauderdale	67	3 S	73.3	722	30.54	177
	Vicksburg	25	11	2425	Warren	45	10 E	67.2	668	9.63	203

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Table A-2 (Continued)

State	Candidate City	City Population 1000's	Area Sq.Mi.	Population Density /Sq.Mi.	County	County Population 1000's	Airport Location Miles	Community Indicators (on a Per Capita Basis) Households with Autos Percent	Value Added by Manufacturing $/Capita-Year	3 Month Payroll Motor Freight & Warehousing $/Capita	Annual Gas Sales $/Capita
Missouri	Springfield	120	62	1950	Greene	153	8 NW	84.8	1380	18.66	138
Montana	Billings	61	15	4190	Yellowstone	87	2 NW	88.7	384	22.67	146
	Bozeman	19	6	2960	Gallatin	33	8 NW	90.7*	242*	3.32	170*
	Butte	23	5	4580	Silver Bow	42	4 SE	80.7*	274*	9.71	112*
	Great Falls	60	15	4100	Cascade	82	4 SW	87.5	552*	13.05	195
	Helena	23	10	2340	Lewis & Clark	33	3 NE	89.1*	412*	4.29	115*
	Missoula	29	8	3730	Missoula	58	5 NW	87.3	679	14.38	303
Nebraska	Lincoln	149	49	3035	Lancaster	168	5 NW	87.5	713	7.02	131
Nevada	Las Vegas	125	51	2440	Clark	273	6 S	89.9	157	4.49	281
	Reno	72	30	2400	Washoe	121	4 SE	85.7	322	15.73	201
New Hamp.	Manchester	88	32	2740	Hillsborough	224	5 SE	75.6	1813	19.68	165
New York	Albany	115	21	5540	Albany	287	8 NW	65.5	847	21.23	93.
	Binghamton	64	11	5830	Broome	222	10 N	73.1	2631	16.69	116
N. Carolina	Fayetteville	53	23	2290	Cumberland	212	5 SE	79.5	760	8.02	193
	Greensboro	144	54	2650	Guilford	289	10 W	83.1	2243	23.05	150
	Kingston	22	6	3720	Lenoir	55	4 N	77.5	1689*	10.92	85*
	Wilmington	46	18	2640	New Hanover	83	3 NE	72.8	1150*	23.23	152
	Winston-Salem	133	56	2350	Forsyth	214	3 NE	78.6	5641	76.64	114
N. Dakota	Bismarck	35	11	3180	Burleigh	40	3 SE	88.5	220	8.41	139
	Fargo	53	12	4640	Cass	74	3 NW	84.7	311	13.69	124
	Grand Forks	39	9	4240	Grand Forks	61	7 NW	86.1	256	8.17	133
	Jamestown	16	10	1585	Stutsman	24	2 NE	89.1	75*	7.07	175*
	Minot	32	8	3985	Ward	59	2 N	88.1	169	7.52	229
Oklahoma	Lawton	74	31	2390	Comanche	108	2 S	90.8	100*	3.73	98
Oregon	Albany	18	7	2600	Linn	72	8 NW	91.1	1554*	11.92	155*
	Eugene	76	26	2925	Lane	213	8 NW	87.8	813	9.08	186
	Klamath Falls	16	6	2630	Klamath	50	5 SE	92.3	722*	8.94	145*
	Medford	28	12	2330	Jackson	95	3 N	84.8	768	12.17	251
	Pendleton	13	5	2750	Umatilla	45	3 NW	88.5	796	6.61	177*
	Salem	68	25	2775	Marion	151	2 SE	83.7	1059	6.24	172
Pennsylvania	Bethlehem	73	20	3730	Lehigh	255	5 NW	81.4	4118	22.07	91
	Scranton	108	26	4030	Lackawanna	234	7 NW	74.1	1520	18.01	74
	Williamsport	38	9	4170	Lycoming	113	5 E	74.4	3676	11.92	94

..... Continued

Table A-2 (Continued)

State	Candidate City	City Population 1000's	Area Sq. Mi.	Population Density /Sq. Mi.	County	County Population 1000's	Airport Location Miles	Community Indicators (on a Per Capita Basis): Households with Autos Percent	Value Added by Manufacturing $/Capita-Year	3 Month Payroll Motor Freight & Warehousing $/Capita	Annual Gas Sales $/Capita
S. Carolina	Columbia	113	33	3400	Richland	234	7 SW	76.5	482	14.85	141
	Florence	26	10	2650	Florence	90	2 E	76.1	869	14.62	223
S. Dakota	Aberdeen	26	6	4730	Brown	37	3 E	85.9	512	7.43	139
	Rapid City	44	16	2660	Pennington	59	9 SE	90.9	330	17.72	162
	Sioux Falls	72	25	2900	Minnehaha	95	3 NW	87.4	858	35.96	132
Tennessee	Chattanooga	119	52	2270	Hamilton	254	10 E	70.0	711	21.22	166
	Jackson	40	17	2310	Madison	66	6 W	75.6	1103	4.74	151
Texas	Amarillo	127	60	2090	Potter/Randall	144	10 E	91.3	377	20.27	167*
	Beaumont	116	72	1620	Jefferson	245	10 SE	84.4	547	10.01	253
	Lubbock	149	76	1970	Lubbock	179	6 N	91.9	589	20.46	134
	McAllen	38	14	2790	Hidalgo	182	2 SW	83.4	171	3.32	201
	Midland	59	29	2035	Midland	65	8 W	93.4	110	13.15	154
	Odessa	78	18	4260	Ector	92	8 W	94.2	590	17.32	154
	San Angelo	63	34	1900	Tom Green	71	8 SW	89.5	678	8.99	145
	Wichita Falls	98	42	2310	Wichita	122	6 NW	89.5	314	5.94	130*
Utah	Salt Lake City	175	59	2970	Salt Lake	459	4 W	81.4	1405	30.97	177
Vermont	Burlington	39	10	3830	Chittenden	99	3 E	77.3	1623	7.06	102
Virginia	Charlottesville	39	10	3740	Albemarle	77	8 N	81.1	403	1.71	143
	Lynchburg	54	25	2160	Campbell	43	6 S	73.9	3261	8.86	168
	Roanoke	92	27	3460	Roanoke	159	4 NW	75.6	976	36.47	140
Washington	Spokane	170	51	3360	Spokane	287	7 SW	81.1	751	11.17	139
W. Virginia	Charleston	71	27	2630	Kanawha	229	5 NE	74.1	1001	23.57	158
	Huntington	74	15	5060	Cabell	107	5 SW	71.8	2454	14.44	110
Wisconsin	Eau Claire	45	20	2240	Eau Claire	67	4 NE	85.8	3018	11.62	149*
	Green Bay	88	42	2100	Brown	158	6 W	87.6	2397	32.91	134
	Madison	173	49	3570	Dane	290	5 NE	81.2	814	6.05	114
	Oshkosh	53	10	5430	Winnebago	130	3 SW	83.3	1777	11.32	114
	LaCrosse	51	15	3365	LaCrosse	80	5 NW	81.0	1922	22.06	138
Wyoming	Casper	39	8	4800	Natrona	51	8 SE	91.5	551*	20.82	128
	Cheyenne	41	11	3590	Laramie	56	1 N	90.0	166*	6.23	178
	Sheridan	11	4	2660	Sheridan	18	2 SW	88.5	311*	28.42	178*
	Mean						$\bar{x}$	83.3	1205	12.92	153
	Std. Deviation						σ	6.56	1177	9.43	46

*County Data.

A.2 Final Selection of a Model City

The following additional criteria were applied to this list of 133 cities to insure that the model city selected contained a representative mixture of various noise sources:

1. A freeway (minimum of one 4-lane highway) system exists;
2. Rail lines pass through town;
3. Manufacturing activity is near the mean for the 133 cities;
4. Motor freight activity is also near the mean;
5. Automobile ownership and usage is near their respective means.

The statistics available to describe the last three categories are: value added by manufacturing per capita, taxable payroll in motor freight and warehousing per capita (normalized by the local mean family income, in an attempt to eliminate the influence of differing costs of living), and percent of households with access to an automobile and per capita expenditures for gasoline. It was decided that the parameters for the model city describing criteria 3 and 4 should be within one-half a standard deviation from the mean and that parameters describing criterion 5 be within one standard deviation.

Application of these criteria produced a list of 11 cities, five of which were eliminated by adding the requirement that mean January and July temperatures be near the national average. The resultant "average" six cities are listed below.

Stockton, California
Macon, Georgia
Peoria, Illinois
Lexington, Kentucky
Jackson, Mississippi
Spokane, Washington

Finally, all other factors being equal, final selection of the model city depends on accessibility and availability of data. Since only Stockton and Spokane are on the West Coast, within a reasonable travel distance from Wyle, and since Wyle has worked closely in the past with a planning firm in Spokane and, therefore, has ready access to community planning information, Spokane, Washington, was the logical choice for the "average" model city for this program.

APPENDIX B

SUMMARY OF ACQUIRED DATA FOR SPOKANE, WASHINGTON

A constraint on the complexity and depth of the environmental noise analysis carried out for this study is the availability of specific data for the experimental city (Spokane, Washington). Fortunately, information on all of the following general categories was available for Spokane:

- Land use — leading to definition of noise criterion for different city areas and definition of "acoustic geography"
- Population distribution throughout the day
- Major noise source definition —
  - Type and location
  - Volume of activity; current and projected

A map of Spokane, Washington, identifying the land use and noise sources throughout the city can be found at the end of this Appendix B.

To facilitate data acquisition, a subcontract was let to a Spokane-based environmental planning firm. The following is an outline of the specific areas where data were obtained, and a summary of the quantity and quality of the information:

1. <u>Definition of Current and Projected Land Use</u>

   a. "Land Use Plan for Spokane, Washington," prepared by the City Planning Commission, April 1968 (contains both current (1968) and future comprehensive general development plans).

   b. Photographs of current (1973) land use for aid in updating earlier maps.

   c. United States Geographical Survey city quadrant map — for topography definition.

d. Miscellaneous other city maps at scales of 1" = 2000' and 1" = 1000'.

e. Ortho-corrected aerial photos (approximately 50 maps) to further aid definition of building density and spacing. (These maps also show topographic elevation contours.)

f. Separate map for the central business district.

g. Selected samples of current land and property values in the proximity of major arterials and freeways.

2. Distribution of Population

a. 1970 Census Block Statistics for Spokane, Washington (HC(3)-261) – defines population per block by census tracts, defines tracts and block locations, gives number of residents per block; also on computer tape. Complete with census tract maps.

b. "Community Shelter Plan and Program," prepared by City and County Offices of Civil Defense, January 1969. Provides peak daytime and nighttime population concentrations by census tract. This is the only available source distribution of the population during day and nighttime periods and in industrial/commercial areas. Similar studies are available for all major U.S. cities. (Note – the current population of Spokane is essentially unchanged since the 1970 census for the time of this study.)

c. Locations and number of persons at "noise-sensitive locations," as follows:

- Nursing homes and boarding homes (with staff and number of patients).
- Enrollments, addresses, types and map locations for public and private schools in Spokane (for Pre-Expo, 1973 enrollments). Unpublished inventory of schools relative to their noise environments expressed in terms of rankings relative to proximity to major highway or aircraft noise sources.

- Locations and sizes of hospitals, nursing homes and boarding homes in terms of staff size and occupant capacity.
- Additional employment statistical data for Spokane County. Present employment statistics by occupation and industry.

d. 1980 Population Projections by 1970 census tracts.

3. Highway Traffic Activity Data

a. 1970 Average Daily Traffic City flow maps for all major highways and freeways.

b. Data on typical heavy truck percentages for arterials and freeways.

c. Summary of hourly traffic volumes at key locations throughout the City — gives sufficient data for development of day/night traffic split.

d. Annotated map of present freeway system giving relative roadway elevation with respect to sideline terrain.

e. Definition of highway lane configurations for major highways and arterials.

f. Projected highway volumes and truck percentages. [An increase in traffic flow volumes — both autos and trucks — at a rate of 5 percent per year through 1978 is projected by the Spokane Metropolitan Area Transit Study (SMATS).]

g. Detailed transit bus schedules for the central business district analysis.

4. Railroad Operations

a. Maps identifying main and major branch lines of Union Pacific and Burlington Northern railways which are the two railroads serving Spokane.

b. Current schedule of AMTRAK operations.

c. Summary of on-line mainline and branch operations activity by day and night, freight and passenger operations. Typical train lengths and speeds through the City.

5. Aircraft Operations

a. FAA summary of typical operations activity at Spokane International Airport (May 1973).

b. Standard approach and departure navigation charts for Spokane International Airport.

c. Definition of standard approach and departure ground tracks (based upon telecon with air controller and tower personnel).

d. Adjustments to the FAA summary data were made based upon discussions with tower personnel. Definition of runway percent utilization factors. Data on level of military operations (estimated 9 percent — F101 Voodoo jets — Air National Guard).

e. Summary of operations data for Fairchild Air Force Base (west of City). Approach and departure activity by aircraft type, definition of standard approach and departure ground tracks.

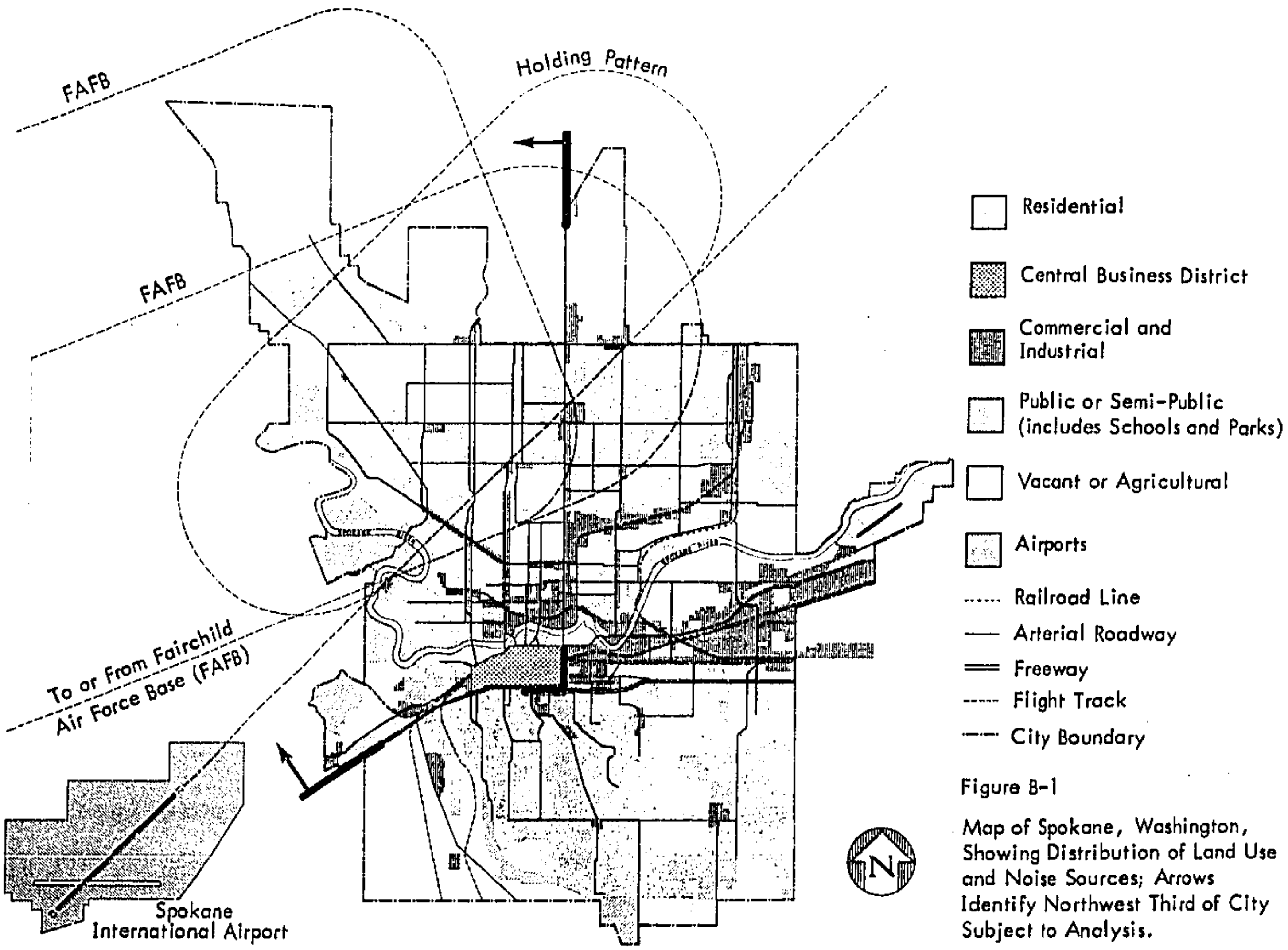

Figure B-1

Map of Spokane, Washington, Showing Distribution of Land Use and Noise Sources; Arrows Identify Northwest Third of City Subject to Analysis.

APPENDIX C

URBAN NOISE PROPAGATION AND POPULATION CELL DEFINITION*

C.1 REVIEW OF DATA ON URBAN NOISE PROPAGATION

The problem of noise propagation in urban areas has been the subject of a large number of investigations. These investigations fall into three groups, i.e., theoretical studies, model studies, and field measurements. The theoretical and scale model studies do not by themselves provide an adequate basis for accurate predictions of field measurements without substantial support by full scale experimental data.[L3, D4] Therefore, this appendix will initially summarize some of these field measurements of urban noise propagation before outlining the particular approach utilized for this study.

C.1.1 Sound Attenuation Along Urban Streets

The attenuation of sound propagating along urban streets has been investigated by a number of workers.[W3, D3, V1, D1, D4] One study examined the attenuation of sound propagating along streets lined with five-story buildings and with 10-story buildings in a similar manner to Figure C.1-1.[W3] For distances up to 1000 feet, the approximate attenuation observed was 6 dB for every doubling of distance.

Reference D3 examined attenuation along narrow streets lined with terraced houses (row houses) as shown in Figure C.1-1. The results indicated an attenuation of approximately 3.5 dB per doubling of distance for distances up to about 20 meters. For greater distances, an attenuation of about 7.5 dB per doubling of distance is indicated, as shown in Figure C.1-2. Other investigations in this area give attenuations of 8 dB per doubling of distance along an urban street for noise produced by a siren[V1]

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*All relative and absolute sound levels in dB are A-weighted levels unless otherwise indicated.

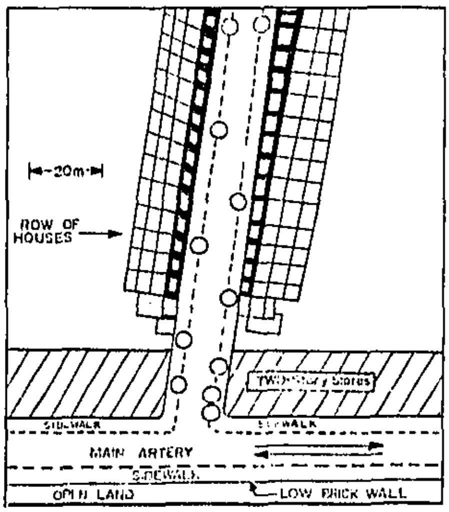


Figure C.1-1. Plan View of Microphone Locations Along a Side Street Leading to Busy Artery (Reference D3).

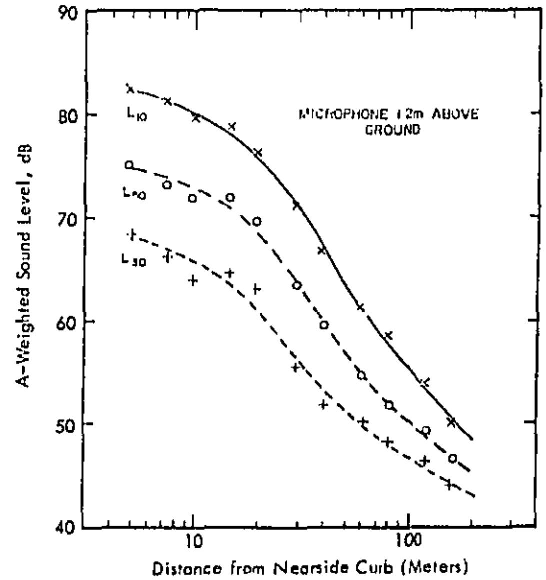


Figure C.1-2. Variation of Noise Level with Distance Along the Side Road for Various Percentile Values (Reference D3).

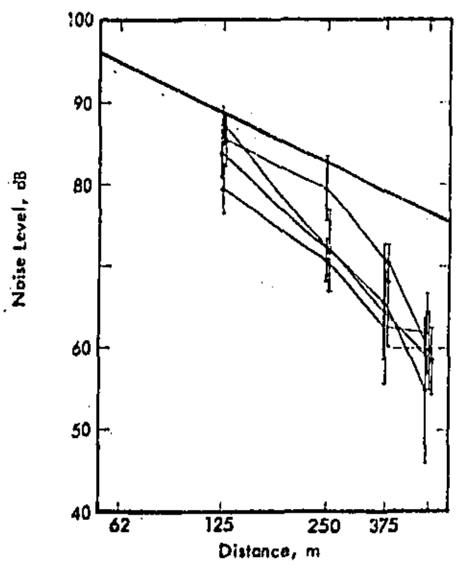


Figure C.1-3. Data Taken Along Streets in Line of Sight of a Siren Source (Reference G8).

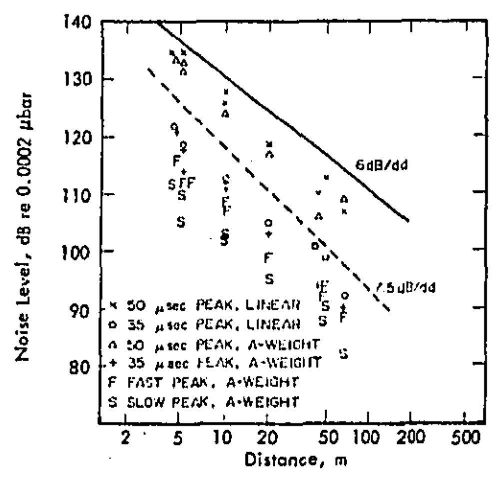


Figure C.1-4. Sound Levels Produced by Pile Driver at Various Distances Along Streets with General Line of Sight to Construction Site (Reference L3).

(see Figure C.1-3) and 7.5 dB per doubling of distance for noise from a pile driver[L3] (Figure C.1-4).

The results of the investigation in Reference V1 on propagation of traffic noise along streets lined with one- and two-story buildings indicate approximately an attenuation rate of about 7 dB per doubling of distance. In general, over the relatively short ranges of interest for this study, wind and temperature effects have not been found to be significant for noise propagation in urban areas.[W3, P1]

C.1.2 Shielding Due to Corners

The reduction in sound has been examined for propagation along streets with the receiver situated around a corner as shown in Figure C.1-5 and not on a line of sight with the sound source. One investigation of the effect of corners found an additional 10 dB reduction in sound levels due to the presence of a corner in the propagation path.[W3] Wyle studies have found approximately 15 dB additional reduction for this effect, while a third examination of this phenomenon found reductions of 10 dB to 20 dB.[V1] For comparison, a theoretical value for this effect was predicted to be only 6 dB.[D1]

C.1.3 Noise Reduction Due to Shielding By Buildings

The problem of acoustical shielding by buildings has been examined by field measurements mostly with the intent of obtaining average values for sound attenuation in urban areas. Average values obtained for the attenuation in excess of geometrical spreading and atmospheric attenuation were as follows.[G6] For residential houses, the excess attenuation for traffic noise was found to be from 3 to 5 dB for each row of houses, as shown in Figure C.1-6, up to a maximum of 10 dB. In the case of a row of terraced houses, the excess attenuation was found to be up to 17 dB. For densely built-up areas, one row of four- or five-story buildings was found to give an excess attenuation of 15 to 20 dB.[F3, K6] In the case of a row of multistory detached houses with a 30 percent open area, an excess attenuation of 10 dB was found for traffic

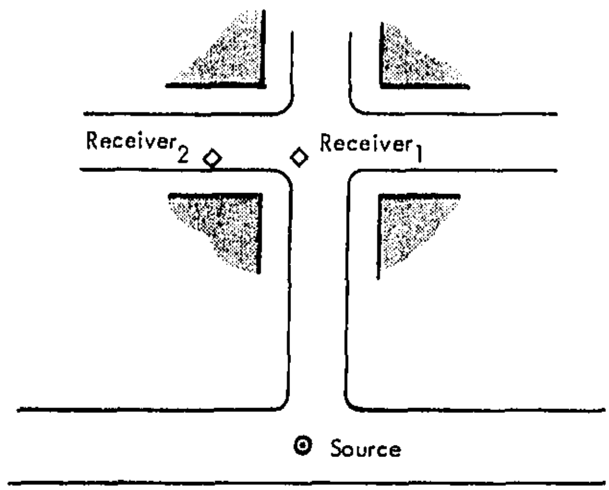


Figure C.1-5. Plan View of Microphone Locations for Measuring the Attenuation Due to Corners

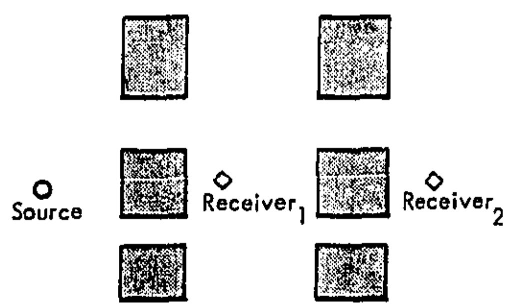


Figure C.1-6. Plan View of Locations for Measuring the Attenuation Due to Rows of Buildings.

noise. Maximum excess attenuations due to shielding by buildings under these conditions has been found to be limited, by scattering effects, to maximum values of about 25 to 30 dB.

C.1.4 Barriers for Sound Attenuation

There have been numerous investigations on the reduction of noise in residential areas by barriers. Since a major source of community noise is vehicular traffic, most of the published work on barriers relates to barriers along highways.[M2, B5, B6] Excellent agreement has been found between field measurements[S12] and predictions based on Reference G6. An attenuation of 5 dB in A-weighted noise levels is easily obtained with a barrier, while an attenuation of 15 dB is obtained only with difficulty. An upper limit to barrier attenuation is also about 25 dB.[B4]

C.1.5 Summary of Field Observations

A few general rules for sound propagation in urban areas can be deduced from the above information. One conclusion is that for streets lined with buildings having from five to ten stories, the attenuation of sound along the street can be assumed to have an average value of 6.0 dB per doubling of distance. Another conclusion is that for streets lined with one- or two-story buildings, the attenuation has an average value of about 7.5 dB per doubling of distance.

An additional attenuation of approximately 15 dB is introduced when the receiving site is situated around a corner from, and not in a line of site with, the sound source.

The attenuation due to shielding by rows of buildings was found to be about 4 dB per row of residential houses with a maximum of 10 dB for multiple rows. For multistory residences, the attenuation was found to be 10 dB for a row of detached houses or up to 17 dB for a row of terraced houses with a practical upper limit of about 25 dB for multiple rows. The attenuation of four- or five-story buildings is similar to that of terraced houses. The attenuation of noise from vehicular traffic by barriers is typically between 5 and 15 dB.

Figure C.1-7 illustrates one example of the net effect of all of these factors which influence urban noise propagation. This shows the fine structure in contours of constant energy-average noise levels measured in an apartment complex area near a freeway. This complexity is taken into account when later in this appendix the procedure is developed for evaluating outdoor noise environments in urban and suburban areas.

C.2 CALCULATION OF NONUNIFORM SPREADING LOSS IN URBAN AREAS

A simple model has been developed conceptualizing the noise propagation conditions in urban areas. It is assumed that the attenuation of noise from vehicular traffic depends only on three variables (see Figure C.2-1): average building height H, blockage (ratio of open space between buildings S to spacing of buildings B), and depth D (distance from source).

Two extreme conditions are defined by $S/B = 0$ (solid walls) and $H \rightarrow \infty$ (infinitely high nonimpervious walls). For the former case, sufficient information exists for calculating the noise reduction by barriers, hills, etc. (for example, References G6, M1, P4, and K3). For the latter case, a simple energy model of sound transmission through leaks and apertures in a composite wall is available.[B2, W4] Noise propagation through building arrays with both finite height and spacing has been treated in a recent theoretical study.[D2] This partially bridges the gap between the two preceding extreme conditions. As far as the depth variable D is concerned, the data reviewed in Section C.1.1 gives sufficient information.

A mathematical formula for the nonuniform spreading loss in urban areas cannot be written down. It is necessary to exercise some judgment in selecting a noise reduction value in a particular situation based on and aided by the above three-variable conceptual model incorporating, as we have seen, theoretical methods and measured data. The rules established and used in the present study are presented after the following discussion on population cells.

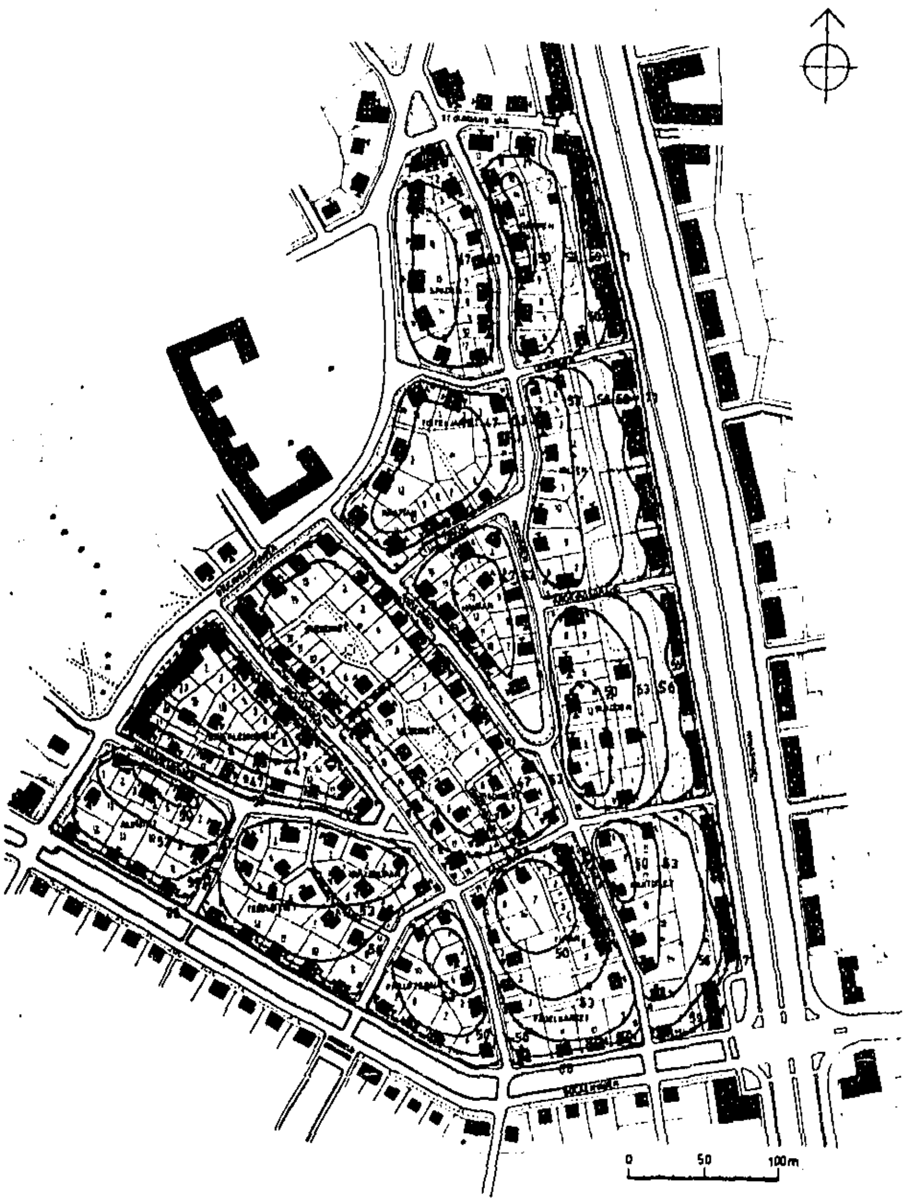


Figure C.1-7. Measured Contours in Enskede, Stockholm of Daytime A-Weighted Energy Average Noise Levels – Each Measured over a 45-Minute Time Period. Contours Spaced at 3 dB Intervals (From Reference N2).

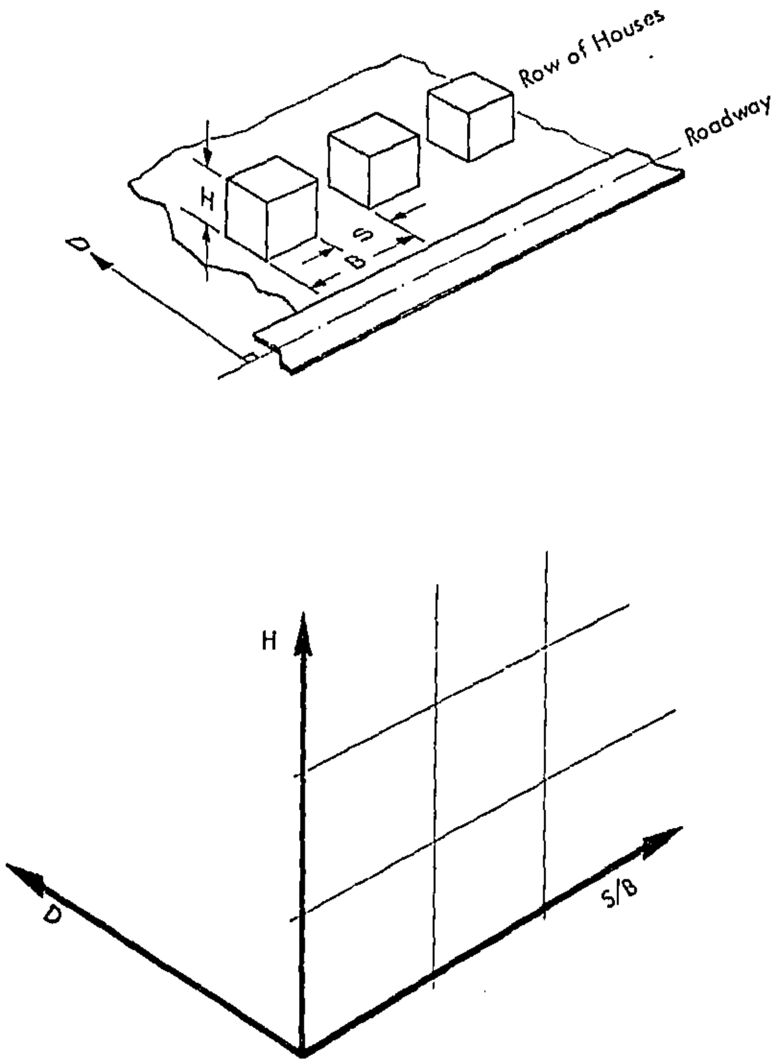


Figure C.2-1. Simple Three-Variable Model for Excess Attenuation Values for Sound Propagation Through Urban Areas. Variables are: H = Building Height, S/B = Open Space Ratio, D = Depth or Distance Along Propagation Path.

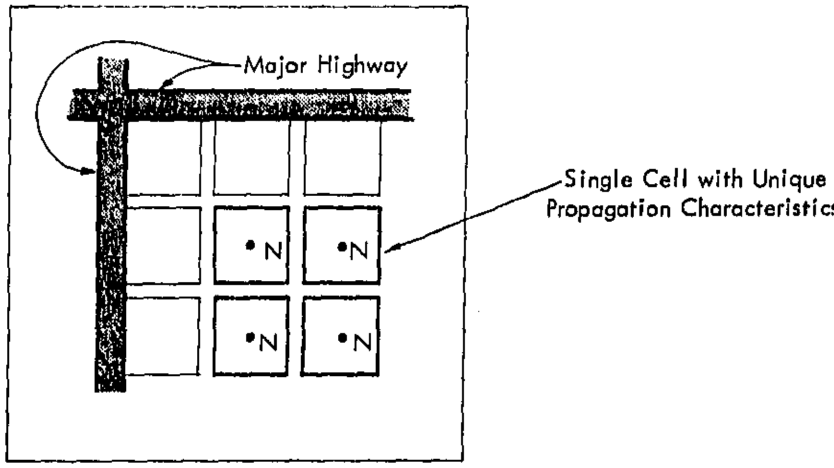
C.3 POPULATION CELLS – SIZE

Strictly speaking, the following discussion applies only to the city selected for this study (Spokane, Washington, see Appendix A). However, the general method can be applied to any similar community noise evaluation. One required step in defining noise propagation conditions is the definition of the receiver locations – that is, the size and central point of each population cell to be considered. The objective is to identify the largest possible groupings of population in the proper proximity to major ground noise sources. The approach is illustrated in Figure C.3-1. Each cell needs to be essentially homogeneous in terms of its "acoustical geography;" that is, the general terrain and building types, if any, should basically be uniform within each cell so that uniform acoustic propagation conditions prevail. For this program, this was initially specified in terms of land use zoning classification of the area, and later further defined in terms of typical building sizes, spacing, and density. Over and above the basic cell structure consisting of a fraction of one block or groupings of several blocks, subcomponents are identified which indicate a particular "noise sensitive" land use, i.e., schools, hospitals, nursing homes, etc.

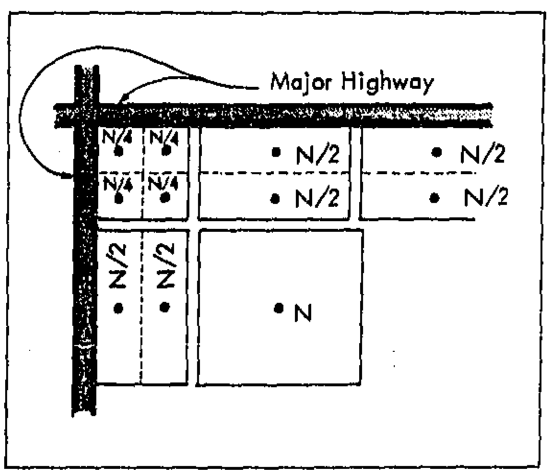
A major problem in establishing cell size is optimizing the balance between accuracy (which dictates smaller population cell sizes) and efficiency in analysis (which dictates larger cell sizes). To evaluate this problem, a brief substudy was made of the sensitivity of the computation of a Noise Impact Index (NII) to size of cells in a hypothetical square segment of the city.

A sample zone was selected in order to facilitate the computations. A simple square zone bordered by four major arterials was deemed the most easily manipulated. For analysis purposes the zone was assumed to be uniformly residential. Hence, variations in land use were not included in this trial evaluation.

The fine system (Figure C.3-2) simulated the most complicated approach and took into account the detailed variation in noise exposure due to traffic flow



a. Location of Block Population, N, for Blocks Not Adjacent to Major Sources



b. For Blocks Adjacent to Major Sources, N is Further Distributed as Shown. For a Typical 300' x 600' Block, this Manipulation of Population Centroid Locations Essentially Place the Residents Within 75 Feet of the Local Major Highway.

Figure C.3-1

differences and receiver distances from the major noise sources. This system was chosen as the standard for comparison of the other systems. The term "exposure distance" was used to denote the effective distance where all the receivers in a cell would have to be placed if the total exposure to noise energy is to stay the same as when they are distributed over the cell. For the fine system the first row exposure distance was set at 75 feet from the roadway; second row exposure was 225 feet and third row exposure was set at 450 feet from the roadway. These values were selected as reasonable estimates of typical dwelling unit spacing in Spokane.

The coarse system (Figure C.3-3) was an extremely simplified approach combining the cells of the fine system together into larger cells. This had the effect of changing the exposure distance to 150 feet. The number of different noise exposure areas was greatly reduced. Variations in traffic flow were neglected. The error in the noise index of the coarse system when compared to the fine system was 10 percent. This was considered an unacceptable error so two other cell configurations were explored.

The simplified fine system (Figure C.3-4) was an attempt to simplify the corner distribution pattern of the fine system. The results indicated that the contribution to the overall noise index of the small corner cells was relatively small. This cell configuration retained the traffic flow variations of the fine system. The first row exposure distance remained at 75 feet, but the second row exposure distance was combined with third row exposure: the typical receiver distance was set at 300 feet from the roadway.

The simplified system (Figure C.3-5) eliminated the minimal effects of the traffic flow variations and combined the corner cells with the edge cells. The first and second row exposure was kept at 75 and 300 feet, respectively.

The simplified fine system produced an error of 2 percent from the standard, but the simplified system produced an error of only 0.7 percent. Although this amazingly small error may have been partly coincidental, it was felt that the

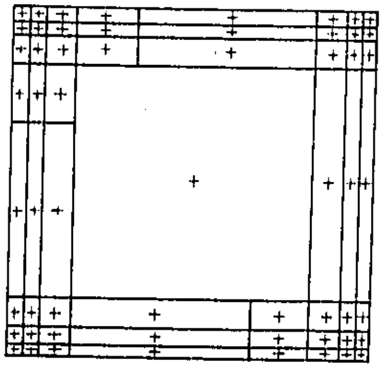


Figure C.3-2. "Fine" System: City Zone Divided Into Large Number of Variable Size Cells (+ = Central Point).

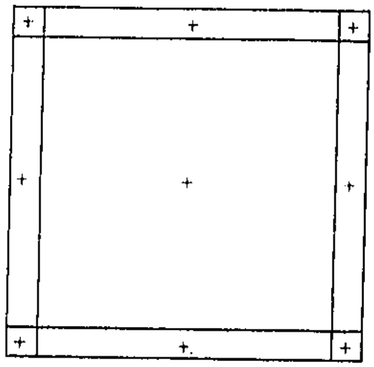


Figure C.3-3. "Coarse" System: City Zone Divided Into a Small Number of Cells.

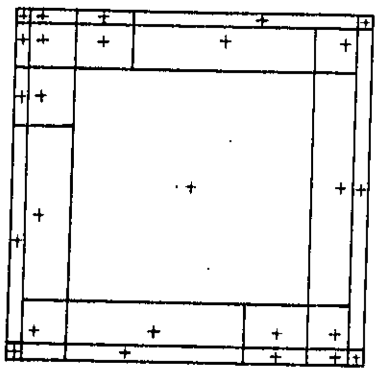


Figure C.3-4. "Simplified Fine" System.

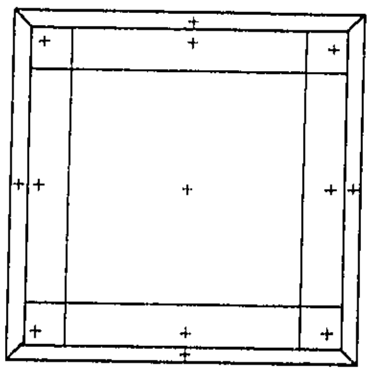


Figure C.3-5. "Simplified" System: Adopted for the Present Study.

simplified system provided the most feasible combination of accuracy and simplicity. It was therefore decided that the simplified system would be the basis for the determination of cell division throughout Spokane. Since real cells cannot always be chosen square like the one in this analysis, some subjective judgment was exercised in the determination of cell shape and of the central point (the "+" in the above figures).

C.4 OUTDOOR SOUND PROPAGATION FOR VARYING DEGREES OF LAND DEVELOPMENT

In keeping with the three-variable conceptual model of urban noise propagation discussed earlier, the noise reduction values are given in this section for the land use zones of Spokane, Washington. The generally flat terrain of that city allows using land use zoning categories alone for defining categories of sound propagation conditions. The zone designations are explained in Table C-1 which also contains some data on building geometry necessary for defining the acoustic geography.

- Single-Family Dwellings (Zones R1 and R2)

Examination of the aerial photos of Spokane reveals a similarity of neighborhood layouts for single family detached dwellings. The majority of the neighborhood geometry may be described as follows.

Residences adjacent to arterials are typically set back 50 feet from the edge of the road. The next row of dwellings is typically 200 feet from the arterial and the third row is typically 400 feet. These buildings typically have a 40 foot frontal width and are normally separated by 15 feet. It is assumed that the majority of these dwellings are single story (15 feet high or 10 feet above the observer).

Based on the data reviewed in Section C.1 and with guidance from references cited in Section C.2, the following values of excess attenuation are selected for Spokane.

Table C-1

Classification of Land Use by Typical Building Structures

Land use classifications for Spokane are presented in the following format:

a. Building height (number of stories)

b. Building frontage

c. Typical spacing between buildings

Zone	Description
R1	Low Density Single Family
R2	Two Family (Duplex)
	a. Single story (15 feet)
	b. 60 feet in length
	c. 30 feet spacing - Spacing Ratio (S.R.) = 50 percent
RO	Residential Office (same as B1)
R3	(Medium Density) Small Apartments (4 Dwellings)
	a. Two story (30 feet)
	b. 60 feet in length
	c. 30 feet spacing - S.R. = 50 percent
R4	High Density (High-rise Apartments)
	a. Three to six stories
	b. 100 feet to 200 feet in length
	c. 30 feet, 60 feet spacing - S.R. = 15 percent to 60 percent
B1	Local Business Zone
	a. One or two story
	b. 100 feet to 200 feet length (several stories)
	c. Zero spacing (except side streets) - S.R. = 0 percent

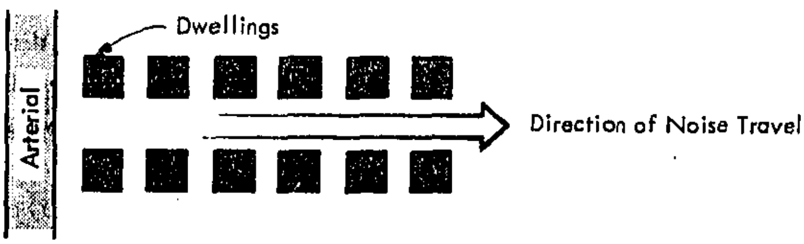
Table C-1 (Continued)

Zone	Description
B2	Community Business Zone a. One or two story b. 600 feet c. Zero spacing (except side streets) - S.R. = 0 percent
B3	Central Business District a. Five to ten stories b. 600 feet length (length of block) c. Zero spacing (except side streets) - S.R. = 0 percent
C1	Commercial Zone a. Five to ten stories b. 600 feet length (length of block) c. Zero spacing (except side streets) - S.R. = 0 percent
M1	Light Industry (Industrial Park and Light Industry) a. Two story b. 100 feet to 600 feet c. Zero spacing (except side streets) - S.R. = 0 percent
M2 & M3	Heavy and Unrestricted Industry a. Two story b. 100 feet to 600 feet c. Zero spacing (except side streets) - S.R. = 0 percent

For a single row of houses: 5 dB

For two or more rows of houses: 6 dB

For the case of propagation down residential streets (see sketch below) the total propagation loss is assumed to follow a 6 dB per double distance law.



- <u>Multifamily, Commercial and Industrial Buildings</u>

For attenuation over nonsingle-story detached residence buildings in Spokane, the following guidelines have been established:

1. Calculate excess attenuation for one row of structures.
2. Since for single-story detached dwellings, the majority of excess attenuation is created by the first row, it is assumed for Spokane that excess attenuation past the first row of multifamily, commercial or industrial buildings does not change.

The following additional guidelines were adhered to for land use Zones R3, R4, RO, B1, B2, B3, C1, C1, M2, and M3 as defined in Table C-1.

- <u>Zone R3:</u>

The total attenuation for sound traveling over R3 structures is expected to be virtually the same as for propagation over R1 and R2 structures.

- Zones R4, RO, B1, B2, B3, C1, M1, M2, and M3:

These structures yield quite different attenuations for the cases of sound propagation over buildings and sound propagation down streets. For these structures, the following rules are used:

1. Determine characteristic orientation of buildings with respect to arterials for that portion of the city (if buildings are parallel, the controlling propagation path is over buildings and if buildings are perpendicular, propagation is primarily down the street).

2. For propagation over buildings, the total attenuation values in Table C-2 were used.

3. For propagation down streets, 6 dB per doubling of distance was used.

Table C-2

Total Attenuation for Sound Traveling Over Buildings
Applied to Analysis of Spokane

Total Adjustment in L_{eq} at 50 Feet Which Accounts for Natural
Losses and Building Shielding (Add Value to L_{eq} at 50 Feet)

Distance from Road	Attenuation* for Flat Terrain	R1 R2 1-Story	R3 2-Story	R4 4-Story	RO B1 B2 1-Story	B3 C1 5-Story	M1 M2 M3 2-Story
50 Feet (1st Row Exposure)	0	0	0	0	0	0	0
200 Feet (Position of 2nd Row with Shielding for 1st Row)	-8	-13	-14	-19	-19	-31	-24
400 Feet (Position of 3rd Row with Shielding by 1st and 2nd Row)	-12	-18	-18	-23	-23	-35	-28

*Relative to L_{eq} at 50 feet.

APPENDIX D

SHORT DESCRIPTION OF THE COMMUNITY NOISE COUNTERMEASURE EFFECTIVENESS COMPUTER PROGRAM

An immense amount of data input and processing is required for analyzing the effectiveness of a given noise countermeasure scenario. A computer program has been written designed to be run on a large computer by a user sitting at a remote terminal and interacting with the computer. A series of commands allows the user to invoke any part of the program at his discretion. The program will notify the user of any gross errors he may commit.

The program actually consists of three programs identified by the three large boxes of Figure D-1. They are self-contained in the sense that they can be executed independently. They are interdependent in the sense that two of them generate input data for the third as is indicated in Figure D-1 by the arrows connecting the large boxes.

The first program (Preparation of Data Base) generates and organizes the basic data as the name conveys:

- The population distribution during day and night (based on U.S. Census information)
- The location, size, and noise sensitivity of each population cell (based on a land use map)
- The location and strength of all noise sources (highways, railways, flight paths, etc.)

The second program (Preparation of Countermeasure Data) creates files with the following information:

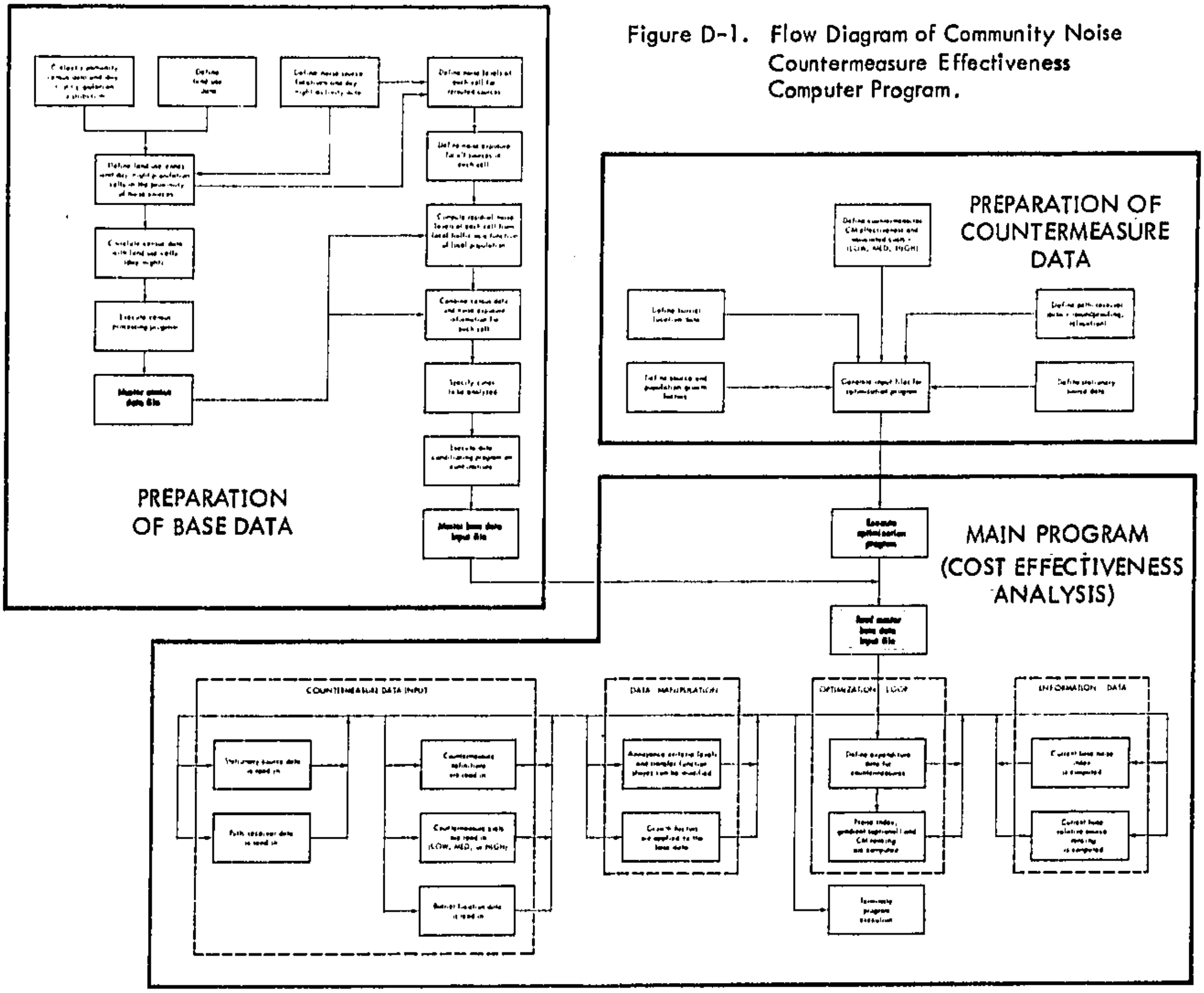


Figure D-1. Flow Diagram of Community Noise Countermeasure Effectiveness Computer Program.

- What countermeasures should be considered
- How much noise reduction is effected given a certain amount of money spent on each countermeasure
- Where barriers could be placed
- Where stationary noise sources are located

The bases for these data are discussed mainly in Chapters 7 and 8.

The third program [Main Program (Cost Effectiveness Analysis)] is used to find out how to spend most efficiently a given amount of money on noise reduction of various sources. For evaluating the efficiency (or effectiveness) of a certain scenario of money spent, a single number is computed: the Noise Impact Index, abbreviated to NII. It is the number of people likely to have an adverse response to the noise environment, divided by the total number of people in the area under analysis. The objective is to minimize NII by spending the available funds in an optimal way, i.e., on those sources whose noise level reduction will decrease the adverse response of the largest number of people possible.

The Main Program uses the data files generated by the other two programs. In addition it must be supplied with information on how many people are expected to have an adverse response given a noise level, a location (i.e., land use: residence, school, office, etc.), and a time of day (day or night). This data is contained in the "transfer functions" discussed in Chapter 3.

It is up to the user of the program to find the most cost effective scenario of money spent by trying different scenarios and observing the trends in NII. The program helps the user in his task by computing gradients: the changes in NII for an additional small amount of money spent on each countermeasure.

Due to the complexity of the problem and the many nonlinearities involved, it was decided not to use an automatic built-in optimization procedure but to use the ingenuity of the user in conjunction with the speed, accuracy, and practically boundless memory of the computer.

APPENDIX E

CORRELATION OF SAE DRIVE-BY NOISE TEST DATA TO OBSERVED HIGHWAY PERFORMANCE OF MOTOR VEHICLES*

E.1 HEAVY TRUCKS

It is desired that a functional relationship be established between the energy-mean noise levels of truck populations under SAE J366b test conditions and noise levels produced over a range of actual observed operating conditions.

The total heavy truck population, comprised as suggested in Table E. 1-1, gives rise to a total energy mean of 90.7 dB under SAE J366b test conditions. Comparing this value with the observed heavy truck noise population distribution (<35 mph) in Washington State as illustrated in Figure E.1-1 [Energy mean = 82 dB] indicates that the composite of noise exposure on an energy basis would be overestimated by approximately 9 dB. As a second point of correlation, consider the computed energy-mean level of 89 dB of the assumed California fleet, also as shown in Table E.1-1. This level corresponds to an energy-mean level of observed low speed heavy trucks in California (Figure E.1-1) of 80 dB; thus also indicating a difference between SAE J366b and observed values of approximately 9 dB.

Thus, this coarse analysis shows that a reduction in energy-mean levels as indicated by SAE J366b test performance will be reflected in the observed noise emission characteristics of heavy trucks operating at low speed (< 35 mph) on a one-to-one basis.

Finally, when one considers the energy-mean noise levels for California and Washington vehicles operating at high speeds computed from the observed populations shown in Figure E.1-2, the level of 88 dB is obtained for each population, thus

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* All relative and sbsolute sound levels in dB are A-weighted levels unless otherwise specified.

implying the dominance of the tire component at these speeds which is not affected by SAE J366b test compliance. The energy-mean levels of both the high- and low-speed populations for California and the Washington heavy truck populations are summaried in Table E.1-2.

Table E.1-1

Analysis of Energy-Mean Noise Levels of Heavy Truck Fleet

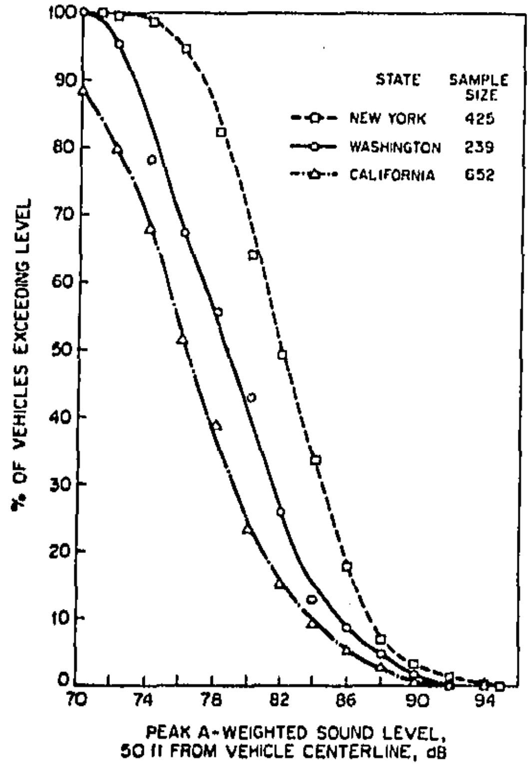
Vehicle Age Group	Percent of Total*	Energy-Mean Level of Population Segments (SAE J366b), dB	
		Assumed National Fleet	Assumed California Fleet
Less than 2 Years	19.5	86	86
2 to 5 Years	42.3	89	88
5 to 10 Years	21.8	92	90
Greater than 10 Years	16.4	94	92
Fleet Mean Energy Level		90.7	89

*Reference U5.

Table E.1-2

Energy-Mean Noise Levels of Populations Shown in Figures E.1-1 and E.1-2

Vehicle Population	Low Speed (< 35 mph), dB	High Speed (> 35 mph), dB
Washington	81.9	87.9
California	80.0	87.5



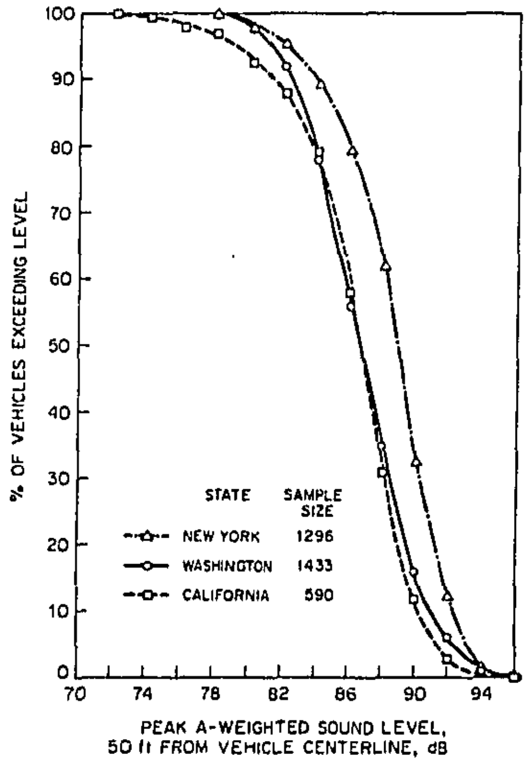


Figure E.1-1. Truck Population Noise Levels at Speeds of 35 mph and Under.*

Figure E.1-2. Truck Population Noise Levels at Speeds Over 35 mph.*

Gross Weights:

California: 6000 lbs and over
Washington: Vast majority of vehicles above 10,000 lbs.

*Sources: References F2, C3, S14.

E.2 AUTOMOBILES

In recent years, emphasis concerning noise reduction of automobiles has centered around reduction of maximum noise output levels under full throttle accelerations as specified by SAE Test Procedure J986a. Thus, nearly all available cost data on vehicle quieting is geared to reducing these maximum levels. Presently, all new product regulations governing noise emission of automobiles is based upon maximum levels as produced by the SAE test procedure. Considering the noise levels emitted by recent and current production automobiles, further noise reductions as indicated by this test procedure are simply not realistic. Extensive studies of driving habits across the entire country by the General Motors Proving Ground Staff have indicated that only approximately 17 percent of the total driving time in urban areas (city streets) is spent accelerating while less than 5 percent of high-speed driving (suburban) is spent accelerating.[G4] A summary of the GM observed driving habits in terms of percentage of driving time spent in the modes of idle, acceleration, deceleration and cruise is presented in Table E.2-1.

Also presented in Table E.2-1 is a summary of the SAE J-1082 Fuel Economy Driving Schedules for Urban and Suburban Driving Conditions. It has been stated by personnel at the Ford Motor Company that these cycles are believed to accurately represent normal driving habits.[F1] A comparison of the GM observed driving cycles and the SAE J-1082 cycles indicates quite a close agreement as to time typically spent in various modes of operation. The data used in this report is taken from the GM cycle.

To arrive at a reasonable correlation between the SAE J986a noise levels and actual noise emitted, it is first necessary to further analyze the time spent in the acceleration mode of these driving cycles. This breakdown is presented in Table E.2-2. As may be observed, the percentage of time spent at wide open throttle (per SAE J986a Test Procedure) - a rate typically greater than 6 to 7 feet/second^2 for most American automobiles, constitutes less than 2 1/2 percent of the time spent accelerating for both the urban and suburban General Motors observed cycles (which is less than 0.1 to 0.3 percent of the total time in the suburban and urban cycles respectively).

Table E.2-1

Passenger Car Operating Mode Summary

Urban Cycle (City Streets)

Operating Mode	Percent Time in Mode	
	GM Cycle[G4]	SAE Cycle[S15]
Idle	14.4	13.0
Acceleration (Average Rate - ft/sec^2)	16.6 (4.1)	9.5 (6.3)
Deceleration (From Average Speed)	16.0 (20.4)	18.5 (23.6)
Cruise (Average Speed)	53.1 (33.4)	59.0 (20.4)

Suburban Cycle (High-Speed Highways and Freeways)

Operating Mode	Percent Time in Mode	
	GM Cycle[G4]	SAE Cycle[S15]
Idle	1.1	3.1
Acceleration (Average Rate - ft/sec^2)	4.7 (3.8)	9.7 (3.7)
Deceleration (From Average Speed)	5.8 (38.5)	11.4 (52.3)
Cruise (Average Speed)	88.4 (56.4)	75.8 (45.3)

Table E.2-2

Passenger Car – Acceleration Mode Analysis

Urban Cycle

GM Cycle		SAE Cycle	
Rate ft/sec^2	Percent Time	Rate ft/sec^2	Percent Time
1.6 - 3.2	55.4		
3.2 - 4.8	34.1	5	36.4
4.8 - 6.4	8.3	7	63.6
6.4 - 8.0	2.0		
8+	0.1		
Average Rate = 4.1 ft/sec^2 Mean Level = 70.8 dB*		Average Rate = 6.3 ft/sec^2 Mean Level = 70.8 dB*	

Suburban Cycle

GM Cycle		SAE Cycle	
Rate ft/sec^2	Percent Time	Rate ft/sec^2	Percent Time
1.6 - 3.2	70.9	3	77.3
3.2 - 4.8	21.7	5	9.2
4.8 - 6.4	5.4	7	13.5
6.4 - 8.0	1.5		
8.0 - 9.7	0.3		
9.7+	0.3		
Average Rate = 3.8 ft/sec^2 Mean Level = 73.8 dB*		Average Rate = 3.7 ft/sec^2 Mean Level = 73.8 dB*	

*Source: Reference C3

Noise emission data for acceleration rates of less than 1/4 g (approximately 8 ft/sec^2) is very scarce; hence, it was necessary to assign typical overall noise levels for automobiles accelerating either under 35 mph (urban) or over 35 mph (suburban) based upon studies conducted by the California Highway Patrol in 1971.[C3] The noise levels used for the urban and suburban cycles represent the energy mean levels of the observed population of 1969 and newer automobiles. In effecting noise reduction countermeasures for automobiles, it is assumed that any reduction in noise level demonstrated by SAE J986a will be directly reflected in observed noise emission during the acceleration mode (except where tire noise constitutes the lower limit for that speed).

The GM data can further be used to compute an "average speed from which acceleration occurs." The details are not reported here. This speed is 40.5 mph for the suburban, and 22.5 mph for the urban criving cycle (used in Section 6.3.5 to compute acceleration noise reduction potential).

Considering next levels of noise emitted during the cruise portion of the urban and suburban driving cycles, the estimated mean A-weighted level of noise generated by the Spokane automobile population (measured at 50 feet) versus vehicle speed is illustrated in Figure E.2-1. These levels are based upon extensive field measurements of automobile passby noise levels and indicate that for the Spokane analysis, a relationship of noise level to speed (over 15 mph) as shown in Eq. (E-1) is appropriate:

$$L_{car} = 74.5 + 30 \log \frac{V}{65} \quad \text{dB} \qquad \text{(E-1)}$$

where V = vehicle speed in mph.

This noise level information has been combined with a detailed analysis of the percentage of time spent in the cruise mode in each 5 mile-per-hour speed band for both the General Motors and SAE urban and suburban driving cycles to yield weighted mean (on a sound energy basis) noise emission levels in Table E.2-3.

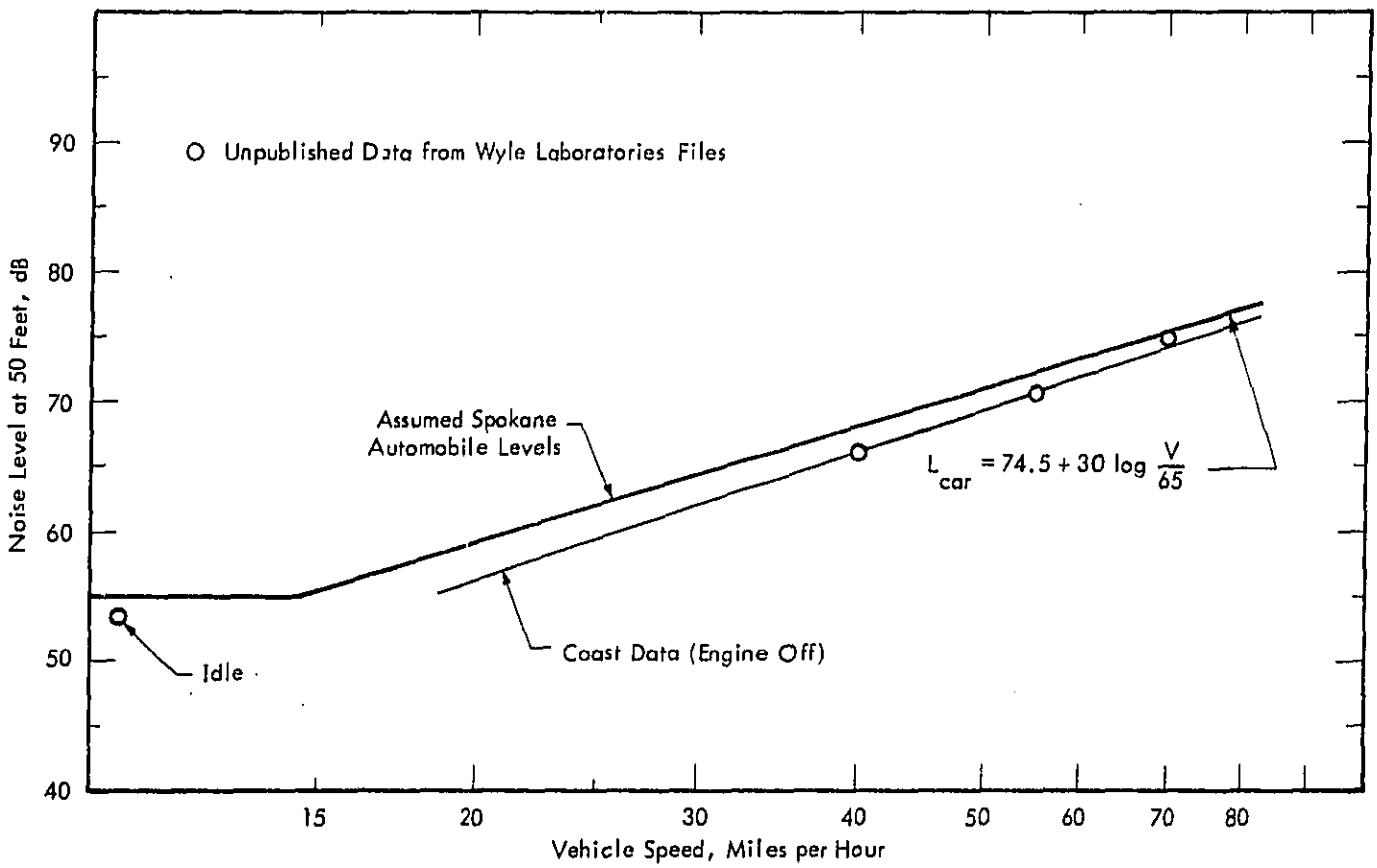


Figure E.2-1. Mean A-Weighted Noise Levels at 50 Feet, Emitted by Automobiles Under Cruise Conditions

The final major noise production driving mode is the deceleration mode. Time spent in this mode for both the GM urban and suburban driving cycles is approximately the same as for acceleration. The noise level emitted during deceleration has been assumed to be that of the cruise level from which the vehicle is decelerating. Hence, an analysis of noise levels for the deceleration mode has been conducted as shown in Table E.2-4 by determining an energy mean noise level weighted by the percent of time the vehicle decelerates from a given 5 mile-per-hour speed band.

In the analysis of automobile noise reduction measures, no noise reductions are reflected in the deceleration mode directly - however, for computation of new mean community noise levels, the mean deceleration level is reduced by whatever value the engine portion of the cruise mode mean level is reduced.

It has been assumed thatnoise levels emitted during the idle mode do not contribute significantly to the total mean noise levels of automobiles during either urban or suburban operation; hence, no noise reductions reflected in the other operational modes are applied to idle conditions.

Given the preceding development of mean energy noise levels by mode of automobile operation and the percent time spent in each mode as given in Tables E.2-1 through E.2-4, we may proceed to compute overall energy mean noise levels for automobiles. This analysis is conducted as shown in Table E.2-5. Hence, we may take the resultant energy mean noise levels as the baseline 1973 condition.

Table E.2-3

Passenger Car – Cruise Mode Analysis

Urban Cycle

GM Cycle			SAE Cycle		
Speed mph	Percent Time	Level* dB at 50 ft	Speed mph	Percent Time	Level* dB at 50 ft
15	11.4	55.5	15	39.0	55.5
20	6.8	59.0	20	28.0	59.0
25	10.4	62.0	25	20.0	62.0
30	16.2	64.5	30	13.0	64.5
35	19.0	66.5			
40	16.0	68.5			
45	10.0	70.0			
50	5.9	71.0			
50+	4.3	73.5			
Average Speed = 33.4 mph Energy Mean Level = 67.3 dB			Average Speed = 20.4 mph Energy Mean Level = 60.2 dB		

Suburban Cycle

GM Cycle			SAE Cycle		
Speed mph	Percent Time	Level* dB at 50 ft	Speed mph	Percent Time	Level* dB at 50 ft
< 30	4.0	64.5			
30 - 40	6.6	66.5	40	56.6	68.5
40 - 50	17.6	70.0	50	33.9	71.0
50 - 60	46.5	72.5	60	9.5	73.5
60 - 70	22.1	74.5			
> 70	3.4	75.5			
Average Speed = 56.4 mph Energy Mean Level = 72.5 dB			Average Speed = 45.3 mph Energy Mean Level = 70.2 dB		

*Computed from Eq. (E-1).

Table E.2-4

Passenger Car – Deceleration Mode Analysis

Urban Cycle

GM Cycle			SAE Cycle		
Speed mph	Percent Time	Level* dB at 50 ft	Speed mph	Percent Time	Level* dB at 50 ft
≤15	44.2	55.5	15	18.2	55.5
20	15.7	59.0	20	22.7	59.0
25	14.3	62.0	25	27.3	62.0
30	11.0	64.5	30	31.8	64.5
35	7.5	66.5			
40	4.1	68.5			
>40	3.0	70.0			
Average Speed = 20.4 mph Energy Mean Level = 62.4 dB			Average Speed = 23.6 mph Energy Mean Level = 62.0 dB		

Suburban Cycle

GM Cycle			SAE Cycle		
Speed mph	Percent Time	Level* dB at 50 ft	Speed mph	Percent Time	Level* dB at 50 ft
≤ 20	18.8	59.0			
20 - 30	15.0	62.0	50	77	71.0
30 - 40	21.3	66.5	60	23	73.5
40 - 50	23.5	70.0			
50 - 60	16.2	72.5			
60 - 70	5.1	74.5			
> 70	0.3	75.5			
Average Speed = 38.5 Energy Mean Level = 69.1 dB			Average Speed = 52.3 mph Energy Mean Level = 71.7 dB		

*Computed from Eq. (E-1).

Table E.2-5

Passenger Car - Community Noise Summary
Typical A-Weighted Noise Levels Produced by Mode of Operation

Urban Cycle

GM Cycle			SAE Cycle		
Mode	% Time in Mode	Energy Mean Level, dB	Mode	% Time in Mode	Energy Mean Level, dB
Idle	14.4	53.5	Idle	13.0	53.5
Acceleration	16.6	70.8	Acceleration	9.5	70.8
Deceleration	16.0	62.4	Deceleration	18.5	62.0
Cruise	53.1	67.3	Cruise	59.0	60.2
Composite Energy Mean Level = 67.1			Composite Energy Mean Level = 63.2		

Suburban Cycle

GM Cycle			SAE Cycle		
Mode	% Time in Mode	Energy Mean Level, dB	Mode	% Time in Mode	Energy Mean Level, dB
Idle	1.1	53.5	Idle	3.1	53.5
Acceleration	4.7	73.8	Acceleration	9.7	73.8
Deceleration	5.8	69.1	Deceleration	11.4	71.7
Cruise	88.4	72.5	Cruise	75.8	70.1
Composite Energy Mean Level = 72.4			Composite Energy Mean Level = 70.7		

APPENDIX F

INDUSTRIAL PLANT, CONSTRUCTION, AND RAPID TRANSIT NOISE COUNTERMEASURES*

Industrial plants and construction sites are stationary noise sources. As such, they can be incorporated into the overall noise countermeasure analysis; the computer program (Appendix D) provides opportunity for specifying the location and strength of stationary sources. Rapid transit lines could be treated as railway lines. However, in the analysis of the noise countermeasure effectiveness of the selected model city (Spokane, Washington) these three noise sources were not considered because:

- The section of the model city analyzed did not have any significant noisy industry
- Construction noise is usually very localized; also, it is virtually impossible to predict locations and strength of construction sources for a period of several years
- Rapid transit does not exist in Spokane

The following discussion is included for completeness and future reference.

F.1 INDUSTRIAL PLANTS

In this Appendix, concern is centered on the community impact of industrial noise. However, in-plant noise reductions effected to comply with OSHA regulations almost invariably would affect the levels transmitted to the community.

The generalization has been made that noise is an undesirable byproduct of the consumption of energy, especially in the performance of mechanical work and that the increase in noise parallels our constant increase in the rate of the national consumption

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*All relative and absolute sound levels in dB are A-weighted levels unless otherwise specified.

of energy. Of all community noise sources, industrial plants present the most extraordinary variety of individual devices and processes, virtually each and all of which possess their own individual noise characteristic.

F.1.1 Industrial Noise Sources

This large variety of industrial sources tends to complicate description. It has been suggested that as a first general division, sources should be classified into five overall groups differentiated by the mechanism of noise production:

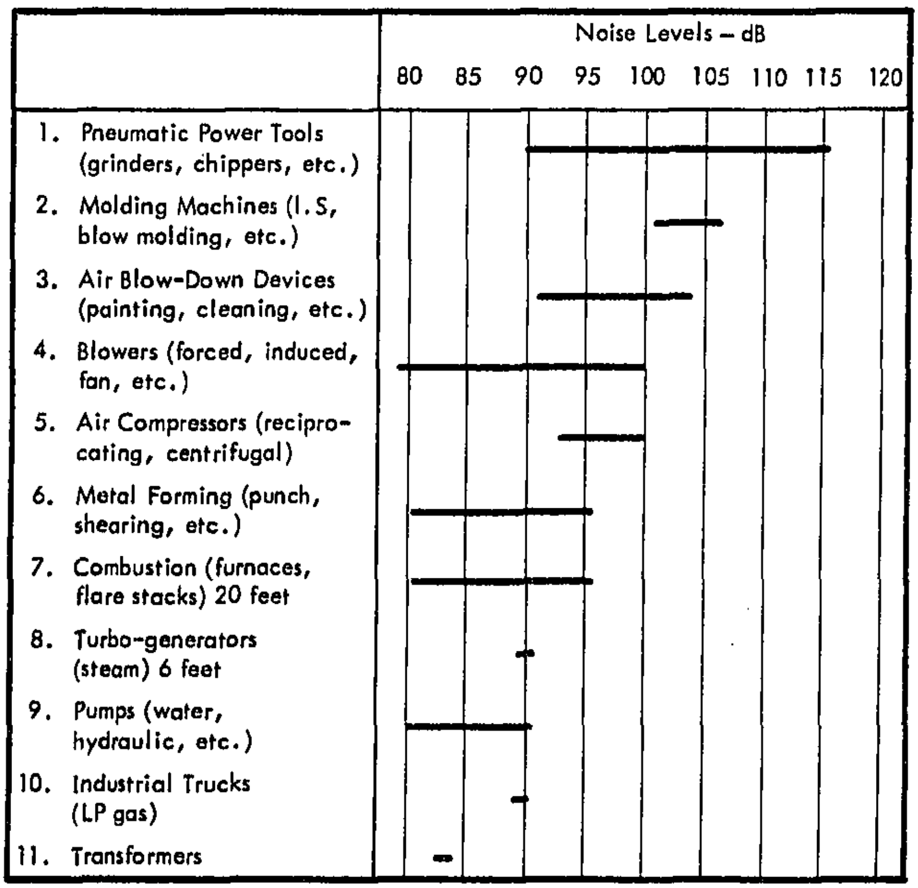
1. Impact
2. Friction
3. Fluid Turbulence
4. Forced Vibration
5. Electro-magnetic

Impact generated noises are of short duration and can be periodic or aperiodic. If periodic, the repetition period is normally considerably longer than the duration of the individual impulses. Impact noise is associated with such processes as forging, punching, shearing, and the like, and is further characterized by unusually high peak levels. Frictional forces generated by the relative motion of machine parts can result in the vibration of associated surfaces producing noise. Fluid turbulence can involve liquids in valves, pumps, hydraulic actuators, etc., and the associated noise is then a result of vibration of the container surfaces. Exhaust pulsations, cleaning and sorting air jets, the blade tip motion of fans and the like can all produce turbulent pressure fluctuations in the air itself which then becomes a direct noise source. Forced vibration again produces noise by the vibration of radiating surfaces or individual machine parts excited by rapid accelerations and decelerations, imbalance in rotating machinery and the like. Electromagnetically induced noise results from the forced motion of such surfaces as transformer cases and motor shells.

Table F.1-1 gives representative in-plant levels (as measured at the operator position) for a variety of industrial machines. Figure F.1-1 gives information even

Table F.1-1

Range of Industrial Machinery, Equipment and Process Noise Levels Measured at Operator Positions (Except Where Noted) (from Reference G5)



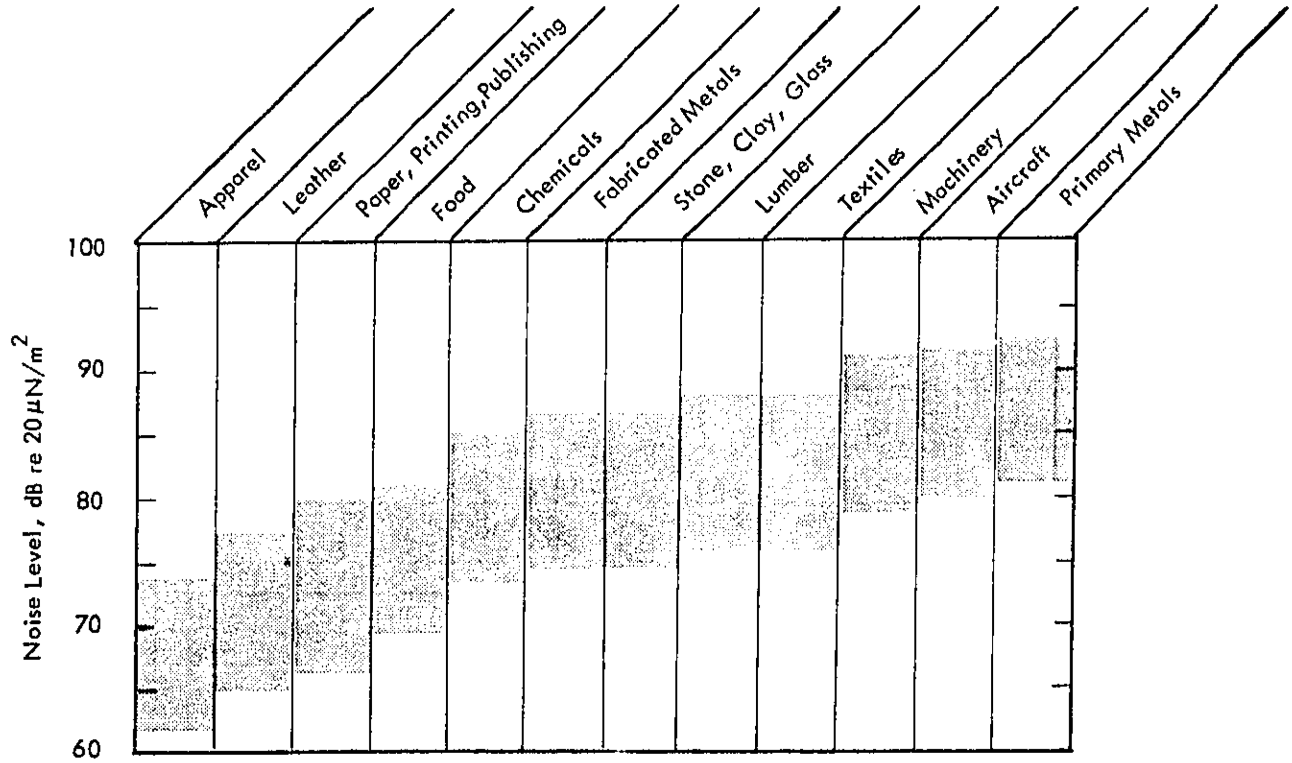


Figure F.1-1. Ranges of In-Plant Noise by Variety of Industry (from Reference B9) more pertinent from the community noise source standpoint, as it rank orders not individual sources, but rather the levels characteristic of different industries. Although the actual levels themselves are again characteristic of in-plant levels rather than property line values, the rank ordering is potentially indicative of community noise contribution.

F.1.2 Sound Path Identification

Direct airborne radiation is the most dominant path to a community for industrial noise. This includes not only radiation through the walls of the plant involved, but also radiation from open windows and doors. Especially in older plants, forced air ventilation may be inadequate or nonexistent. Such ventilation requirements, material handling requirements, etc., often make it impossible to assure window and door closure.

Reverberant paths are not often important to the external propagation but they can seriously affect the build up of in-plant noise which can then affect exterior levels.

Secondary reradiation from external structures excited by transmitted vibrations can become important with heavy operations such as forging. Such a combination of noise and vibration is always unusually disturbing.

F.1.3 Receivers

The effect of industrial noise on individuals who are located nearby by virtue of their work is closely related to the noise environment characteristic of the work involved. If the work activity involves another industry of comparable noise level no significant intrusion would be expected. On the other hand, if the noise environments and tasks are very different, serious interference can result. An interesting special case of this variety involves the office and engineering activities of companies with very noisy manufacturing operations and further, one with all functions located together. Special soundproofing measures are often needed and this may well be one factor involved in the modern tendency to separate the locations. The effect of industrial noise on nearby residents has been shown to be greatly dependent on whether or not the noise:

1. Is continuous;
2. Interferes with speech communication;
3. Includes pure tones or impacts;
4. Varies rapidly;
5. Interferes with getting to sleep; and
6. Contains fear-producing elements.

F.1.4 Industrial Noise Countermeasures

Table F.1-2 outlines general countermeasure techniques for source abatement based on the five general divisions by source mechanism mentioned above.

Table F.1-3 outlines overall procedures for the total control of the impact of industrial plant noise on the community. The major difficulty with the techniques of Group V, Control of External Plant Noise, is that they are usually only economically and operationally feasible when new plant construction is involved.

Table F.1-2

Basic Techniques for Machinery Noise Control at the Source

Impact	– Reduce Deceleration, Damp Source Pieces, Reduce Hardness of Impacting Surfaces, Reduce Size of the Source.
Friction	– Damp Source Pieces, Reduce Hardness or Rubbing Surfaces, Reduce Source Size, Lubricate Surfaces.
Fluid (Air Turbulence	– Reduce Air Velocity, Remove Obstructions, Polish Rough Surfaces.
Forced Vibration	– Balance Parts, Reduce Acceleration, Add Tuned Dampers, Operate Off-Resonance.
Electro-Magnetic	– Reduce Leakage Flux, Remove Nearby Magnetic Materials, Orient Magnet for Minimum Coupling.

Table F.1-3

Noise Reduction Methods

I. Plant Planning a) Selection of Equipment b) Location of Equipment within the Plant c) Location of Plant with Respect to the Community
II. Control at the Source a) Maintain Dynamic Balance b) Minimize Rotational Speed c) Decouple the Driving Force d) Reduce Velocity of Fluid Flow e) Reduce Turbulence f) Use Directionality of Source
III. Control of the Transmitted Noise a) Vibration Isolate the Source b) Enclose the Source c) Absorb Sound within the Room d) Use Reactive or Dissipative Mufflers
IV. Control of Radiated Noise by Partitions, Panels and Walls a) Increase Mass b) Increase Stiffness c) Shift Resonant Frequencies d) Add Damping e) Reduce Surface Area f) Perforate the Surface
V. Control of External Plant Noise a) Acoustically Isolated Ventilation and Air Conditioning b) Sealed Doors c) Double Glazed Windows
VI. Minimization of Residual Noise Impact a) Adequate and Rigidly Enforced Zoning Provisions

F.2 CONSTRUCTION

Construction noise, as with any other community noise problem, produces an overall impact influenced not only by its character, but also directly related to the number of people affected. It is for this reason that the construction of even a major highway can have a far less serious impact than the building of a single, large high-rise structure in the central city. Indeed, this difference is so great that highway construction will not be considered in this discussion, as the major portion normally occurs in thinly populated areas.

The basic unit of construction activity is the construction site and it is true that this exists both in space and in time. When the construction job is completed, the associated noise ceases to exist; further, the noise characteristics can vary as the task proceeds. However, it has been suggested that especially in urban centers the transient character of construction activity is often overrated for at least two reasons. First, when the community as a whole is considered in times of economic progress, the completion of activity at one site is supplanted by startup at another so that from an overall viewpoint, the general problem never ceases. Second, with major projects often 1 or 2 years of activity are involved so that the duration cannot be truly considered short-term.

F.2.1 Construction Noise Source

As with so many outdoor sources, construction equipment noise has become relatively dominated by the internal combustion engine. This general category can be divided into three major areas: earth-moving equipment, materials handling equipment, and stationary power sources.

Earth-moving equipment, as the name implies, is quite mobile and includes bulldozers, front loaders, shovels, back hoes and the like, as well as highway building equipment such as graders, scrapers, compactors, etc. Engines are usually the dominant sources. Tire noise is usually of no consequence at the low speeds usually encountered with construction equipment, so that noise control problems involved are not unlike those for a heavy duty truck. Specific subsources involved are exhaust, fan, air intake, mechanical noise radiated directly from the engine body, transmission, etc., as well as noise unique to the individual function of the unit. Characteristic levels at 50 feet range from 75 to over 95 dB.[B7]

Engine-powered materials handling equipment includes such devices as cranes, derricks, and concrete mixers. Again, engine noise is often the most predominant. Characteristic levels at 50 feet fall in the range of 75 to 90 dB.[B7]

Stationary power sources include generators, air compressors, pumps, and the like. In this class, air compressors were and probably still are the most noisy, ranging formerly up to and beyond 90 dB; however, recently specific noise reduction efforts have been employed with air compressors, the most successful being the use of an enclosing shell-like structure. As a class, therefore, the characteristic range of noise levels at 50 feet has been reduced to 70 to 80 dB.[B7]

Of all the tools and machines which are not usually powered by large internal combustion engines, two classes are worthy of special mention, as they stand far above the rest — saws and impact tools. Although both are very noisy, the latter group, impact tools, are generally conceded to have the highest output of all categories.

The largest of the impact tools is the pile driver which can be steam or diesel actuated when of the basic impact variety. Both the steam exhaust or the combustion explosion that lifts the hammer with diesel units are secondary noise sources. The impact of the hammer is, of course, the major source and because of its impulsive character is difficult to measure and standardize as it is affected by the type of piling being driven, its length, shape, and type of soil. However, peak levels of 100 to 105 dB at 50 feet are common.

This impact noise is absent in the so-called "sonic" or vibratory pile drivers. These units effect a tremendous noise reduction, but are not without other problems including some limitations on the type of soil in which they can effectively function. Three-sided enclosures have been used with the impact variety of pile driver with some success and peak reductions of 12 dB have been achieved.

Very high noise levels of 80 to 100 dB at 50 feet are also characteristic of the smaller impact tools such as jackhammers, pavement breakers, and rock drills. Table F.2-1, compiled from limited data, illustrates characteristic individual noise level ranges for a small variety of equipment of the categories just discussed.

F.2.2 Receivers

Receivers can conveniently be divided into three classes on the basis of the reason for their proximity to the construction site and are:

1. Casual passby
2. Residence near construction site
3. Place of work near construction site

Unless the construction activity is of such a relatively unusual variety that it must proceed throughout the night and therefore could interfere with sleep, work activities near construction sites usually present the most severe problem. Not only is it often more difficult to arrange a "break" away from the noise impacted area, but also the degree of concentration demanded is often higher for the work related case.

F.2.3 Path Description

1. Most common is direct airborne transmission, and this is usually the most important.
2. Under some conditions, however, reverberation fields and transmission by multiple reflection paths can become of almost equal importance. This is especially true for the important case of construction undertaken in the central city on a site completely surrounded by high-rise buildings. It must be remembered that the front and sides of high-rise buildings present almost ideal reflecting surfaces with the surface of each building perfectly parallel to the next. For example, when pile driving occurs under such circumstances, it is not uncommon for each subsequent impact to happen well before the reflecting echoes of the preceding impact have abated.

Table F.2-1

Typical Noise Levels Produced by Construction Equipment
(From Reference B7)

Internal Combustion Engine Powered Equipment	Noise Level at 50 Feet dB
Earth-Movers	
Compactors	72 - 75
Backhoes	72 - 93
Front Loaders	72 - 85
Tractors	76 - 95
Scrapers	80 - 92
Material Handling	
Concrete Mixers	75 - 88
Cranes	76 - 88
Stationary Power Sources	
Generators	72 - 82
Compressors	74 - 88
Impact Equipment/Saws	
Pile Drivers	95 - 106 peak
Jackhammers & Rock Drills	82 - 98
Impact Wrenches	84 - 88
Saws	72 - 84

3. Another major path can also make serious contributions especially when heavy operations are closely coupled to the soil such as digging and pile driving. This is the secondary reradiation of sound from adjacent structures excited by transmitted vibration. The noise produced by vibrating walls, floors, rattling windows and the like is most seriously annoying because of the associated building tremors. Task interference within the affected building can be very high.

F.2.4 Construction Noise Countermeasures

Two major countermeasures are possible: the use of portable barriers and reductions in the source devices themselves.

The only specific data located on the use of barriers for construction noise concerned two tests conducted in cooperation with the Department of Environmental Control of the City of Chicago. The first concerned the use of a three-sided barrier used in conjunction with pile driving. Reductions of 12 dB in the peak impulse levels were claimed. The second gave a more detailed description of an experimental enclosure manufactured by Singer Partitions, Inc. of Chicago. This enclosure measured 9 by 7 by 6 feet and was four-sided with a separate top. Six freestanding columns supported a framework of overhead roller curtain track. Lead filled, vinyl-coated fiberglass curtain material with an inner coating of absorbent acoustic foam was hung from rollers on the track. Similar material was used for a separate roof section to effect a tight closure. It was possible for two men to install the enclosure in 45 minutes. The cost was estimated at $1500, including hardware and roof.

At the time of the test, the ambient noise level was 76 dB. For the test, workmen cut a 12-inch diameter, ductile iron water main with a gasoline-powered saw. Without the enclosure, the measured sound level was 97 dB at 10 feet. With the enclosure in place, a 12 dB reduction to 85 dB was produced.

Because of the contributions of gasoline and diesel engines to construction noise, it is important to consider specific countermeasures to these power plants. This subject is treated in detail in Section 6 on Motor Vehicles Noise Countermeasures.

Table F.2-2 presents estimates for noise levels at 50 feet for a variety of construction equipment, both in terms of present performance and with feasible noise control.

Finally, it is interesting to note two examples of legal restriction on construction equipment performance. In both cases, levels are to be obtained at 50 feet in accordance with SAE Standard J952a:

- A quotation from Section IX, Noise and Vibration Control, Subsection 9.11, "New Motor Powered Equipment Noise Performance" (of the Cook County, Illinois, Environmental Control Ordinance, which is essentially identical to that of the City of Chicago):

9.11 New Motor Powered Equipment Noise Performance

No person shall sell or lease, or offer for sale or lease, any powered equipment or powered hand tool that produces a maximum noise level exceeding the following noise limits at a distance of 50 feet under test procedures established by Section 9.30 of this Article:

Type of Equipment		Noise Limit
(a) Construction and industrial machinery, such as crawler-tractors, dozers, rotary drills and augers, loaders, power shovels, cranes, derricks, motor graders, paving machines, off-highway trucks, ditchers, trenchers, compactors, scrapers, wagons, pavement breakers, compressors, and pneumatic powered equipment, etc., but not including pile drivers:		
Manufactured before	1 Jan. 1973	94 dB
Manufactured after	1 Jan. 1973	88 dB
Manufactured after	1 Jan. 1975	86 dB
Manufactured after	1 Jan. 1980	80 dB

Table F.2-2

Noise Reduction Potential for Construction Equipment
(From Reference B7)

Equipment	Noise Level at 50 Feet, dB	
	Present	Feasible with Noise Control
Earth-Moving		
Front Loader	79	75
Backhoes	85	75
Dozers	80	75
Tractors	80	75
Scrapers	88	80
Graders	85	75
Material Handling		
Concrete Mixer	85	75
Concrete Pump	82	75
Crane	83	75
Derrick	88	75
Stationary		
Pumps	76	75
Generators	78	75
Compressors	81	75
Impact		
Pile Drivers	101	95
Jackhammers	88	75
Rock Drills	98	80
Pneumatic Tools	86	80
Other		
Saws	78	75
Vibrators	76	75

- Table F.2-3 illustrates the restrictions imposed by the General Services Administration for noise performance of construction equipment employed by any Federal construction contractor.

Table F.2-3

Maximum Allowable A-Weighted Noise Levels at 50 Feet
(Re SAE Standard J952 and SAE Recommended Practice J184)

Equipment	Effective 7/1/73	Effective 1/1/75	Equipment	Effective 7/1/73	Effective 1/1/75
Earthmoving			Stationary		
front loader	79	75	pumps	76	75
backhoes	85	75	generators	78	75
dozers	80	75	compressors	81	75
tractors	80	75			
scrapers	88	80	Impact		
graders	85	75	pile drivers	101	95
truck	91	75	jack hammers	88	75
paver	89	80	rock drills	98	80
Materials Handling			pneumatic tools	86	80
concrete mixer	85	75			
concrete pump	82	75	Other		
crane	83	75	saws	78	75
derrick	88	75	vibrator	76	75

F.3 RAPID TRANSIT

Rapid transit noise and railroad noise have one great similarity; for each, a major source is wheel/rail interaction. There are also many important dissimilarities and probably the most central to the community noise problem is the extensive difference in the community diffusion of the right of way. For a rapid transit line to serve a community its stations must be available throughout the community and its tracks must interlace the community. In general, rapid transit lines tend to fan out from the city center, thus affecting more of the central community than railroad lines. Some rapid transit lines penetrate the suburbs, but the far suburbs at least are as likely or more so to be served by commuter rail service. Other differences of note include the following:

1. Each car of a rapid transit system has its own propulsion so that noise emission is distributed equally along the entire train, unlike railroad trains, the propulsion source for which is located in discrete elements, often only at the front.

2. Railroad right of way is most usually found at grade; rapid transit tracks can very often be found below grade (subways) or above grade (elevated).

3. Although traffic on each tends, of course, to peak at rush hour, rapid transit service is usually somewhat more continuous throughout the day than railroad passenger service. Railroad freight haulage tends to be distributed throughout the day on a fairly continuous basis.

F.3.1 Subsource Identification

1. By far the most significant source is wheel/rail interaction. The sound intensity is related to the irregularities encountered. Switches usually make more noise than joints and wheel flats which, in turn, make more noise than small waviness in track or wheel (the so-called micro-irregularities). These are all secondary to the singular effect of wheel screech encountered in curves.

2. Propulsion system noise.

3. Secondary re-radiation of sound from vibration excited structures (important to car interior noise and wayside noise near elevated structures).

4. Reverberation fields in underground stations and tunnels.

5. Singular, noncontinuous noises such as wheel squeal on curves, air brake exhaust, and door closure.

F.3.2 Receiver Identification

It has become a convention group the condition of the receivers into three classes:

1. Passengers and employees in stations.
2. Passengers and employees in the cars.
3. Wayside residents.

F.3.3 Sound Path Definition

1. Direct airborne radiation affects all receivers including passengers by direct transmission through the car shell.

2. Secondary re-radiation by vibration transmission also affects all receivers; it is of particular importance to interior car noise and to noise from elevated lines.

3. Reverberant fields greatly affect station noise and interior car noise when underground. Reverberant fields are both a sound path and a secondary source.

F.3.4 Rapid Transit Noise Countermeasures

Countermeasures are most conveniently divided into those applying to treatment of the cars and those which affect the right of way including stations, as well as wayside noise conditions.

After each countermeasure will be noted a 1, 2, or 3 or a combination thereof to denote that the countermeasure affects 1) in-station noise; 2) interior car noise; 3) wayside noise, or combinations thereof.

Car Treatments

1. Wheel grinding and trueing (1, 2, 3) – (note: as will be indicated with rail grinding such good maintenance procedures are of paramount importance to noise reduction).

2. Reduce the unsprung mass (1, 2, 3) – [the unsprung mass including traction motors, which are elastically mounted only on the Berlin subway (one of the quietest in the world), directly affects the impact produced by any wheel/rail irregularity or discontinuity].

3. Damped and/or resilient wheels (1, 2, 3) – (the effect is more pronounced for wheel screech on curves and there competes with track lubrication; gains are secondary to 1 and 2).

4. Seal doors and double glaze windows (2).

5. Acoustically enclose and forced-air ventilate motors (1, 2, 3).

6. Muffle air brake and door mechanism exhaust (1, 2, 3).

7. Improve motor-gearing for less noise (1, 2, 3).

8. Increase interior car sound absorption (2).

9. Increase transmission loss of car shell and vibration isolate floor of car (2).

Right of Way Treatment

1. Grind and true track (1, 2, 3) – of primary importance.

2. Weld rail or improve joints (1, 2, 3).

3. Lubricate curves (2, 3, sometimes 1) – must not affect into curve breaking.

4. Resilient rail mounting (1, 3, somewhat 2) – (note: this step apparently is useful only up to a certain point; beyond this, noise will actually increase due to freedom of rail to vibrate in a "string" mode).

5. Resilient mounted concrete slab under tracks (1, 3).

6. Trackside barriers (3) – (note: when of adequate height to have significant wayside effect then, unfortunately, an increased reverberant field outside the cars is produced. This should be countered by applying absorptive material on the inside of the barrier).

7. Damping of elevated structures or construction by reinforced cement rather than steel only (some 2, large 3).

8. Absorptive treatment of underground stations, sidewalls and ceiling of tunnels (1, 2).

Costs and Reduction Potential

Representative costs and potential reductions were taken from a study concerned specifically with the Boston system; i.e., Massachusetts Bay Transit Authority. However, the general magnitudes involved are probably roughly representative of other systems. See Tables F.3-1 and F.3-2.

Table F.3-1

Approximate Costs of Noise Reduction Treatment for Rapid Transit Railroads – Car Treatment

Noise Reduction Technique	Reduction Potential	Initial Cost	Maintenance Cost
Damped/Resilient Wheels	1 - 2 dB	\$1000/\$5000 Add Damping/New Wheels	--
Interior Car Abosrption	3 dB	\$1000/car	--
Improve Acoustic Seals	5 -10 dB	\$100/car	--
Wheel Trueing	5 - 7 dB	\$250,000 for Trueing Machine	\$100/car per year
Door Mechanism Repair and Maintain	10 dB	\$600/car	\$30/car per year
Air Brake Muffling	15 dB	\$ 50/car	--
Improvement on a New Car Specification Basis			
Interior Absorption	5 dB		
Acoustical Sealing All Openings	10 dB		
Trued Wheels	5 - 7 dB		
Improved Quieter Door Actuators	10 dB	\$350,000	
Air Brake Vent Muffling	15 dB	per car	
Double Glazed Windows	2 dB		
Car Wall Panel Damping	5 dB		
Quieter Transmission Gearing & Motor	10 dB		
Vibration Isolated and Quieted/ Enclosed Auxiliaries	10 dB		
Improved Vehicle Suspension	10 dB		

Table F.3-2

Approximate Costs of Noise Reduction Treatment for Rapid Transit Railroads – Line Treatment

Noise Reduction Technique		Reduction Potential	Initial Cost	Maintenance Cost
Welded Rail (Joint Elimination)		6 to 8 dB	$ 25/ft	–
Improved Joints		5 dB	$ 5/ft	–
Rail Grinding		8 dB	$400,000 (Estimated Cost of Grinder)	$2/ft per Year
Curve Lubrication		15 dB	$4,000/curve	–
Adjust and True Track Geometry		5 dB	–	
Resilient Rail Fasteners		5 dB at grade 10 dB elevated	$ 8/ft	$2/ft per Year
Resiliently Mounted Concrete Slab		15 to 20 dB	$300/ft	–
Barriers	Nonabsorptive Absorptive	10 to 14 dB 12 to 16 dB	$ 80/ft $100/ft	–
Damping of Steel Elevated Structures		8 to 12 dB	$100/ft	–
Absorptive Treatment in Tunnels	Side Walls Ceiling Both	5 dB 5 to 9 dB 10 to 12 dB	$ 32/ft $ 18/ft $ 50/ft	Assuming No Water Damage
Station Treatment	Ceiling Walls	7 dB 5 dB	$160/ft $ 64/ft	Assuming No Vandalism Destruction
Additional Absorption	Under Platform Concrete Invert	5 to 7 dB 5 dB	$ 16/ft $ 18/ft	– –
Absorptive Barriers Between Tracks		12 to 16 dB	$ 25/ft	–

APPENDIX G

PRESENT VALUE ANALYSIS OF HEAVY TRUCK NOISE REDUCTION COSTS*

This Appendix should be read in conjunction with Chapter 7, Section 7.5 of the main text. The first two sections are concerned with noise reduction measures at low speed. The third section deals with high speed tire noise.

The allocation of heavy trucks to Spokane is conducted slightly differently from that for automobiles. Rather than using registered vehicles as a guide, the percentage of heavy truck mileage in the State of Washington to the total United States is used to determine the heavy truck fleet for the State. This number is then factored by the Spokane County to Washington State population to arrive at the number assigned to Spokane as follows:

$$\begin{pmatrix}\text{Number of 1973}\\ \text{Heavy Duty Trucks}\\ \text{Assigned to Spokane}\end{pmatrix} = \begin{pmatrix}\dfrac{\text{Truck Miles in Washington}}{\text{Truck Miles United States}}\end{pmatrix}\begin{pmatrix}\text{Number of}\\ \text{Heavy Trucks}\\ \text{in United States}\end{pmatrix}\begin{pmatrix}\dfrac{\text{Population of Spokane County}}{\text{Total Washington Population}}\end{pmatrix}$$

$$= (0.007^{**})(1.5 \times 10^{6^{**}})\frac{283,077^{***}}{3,352,892^{***}} = 886 \qquad \text{(G-1)}$$

G.1 INCREASED NEW PRODUCT ACQUISITION COSTS

The consumer costs for new production units to achieve reduced noise levels (re: SAE J366b) are presented in Figure G.1-1. Effects on increased operation and maintenance expenses are summarized in Table G.1-1. The sequel develops the present value cost analysis to achieve the levels of noise reduction identified in Chapter 6 by Cases 1 through 7 of Figure 6.2-1.

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* All relative and absolute sound levels in dB are A-weighted levels unless otherwise specified.

** Source: Reference U5

*** Source: Reference U3

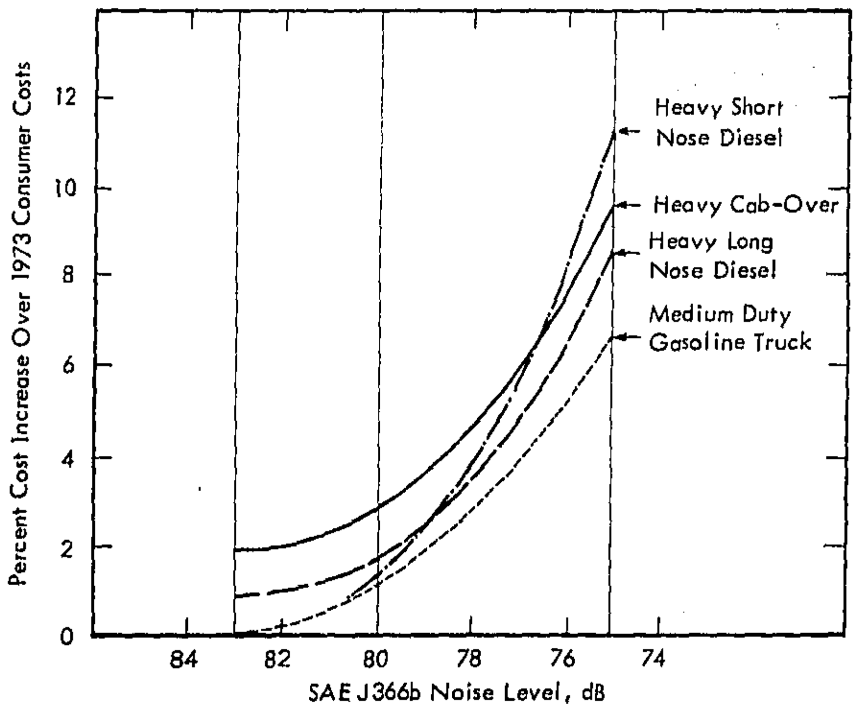

Figure G.1-1. New Production Heavy Trucks: Costs to Consumer for Reduced Noise Emission. Assumed is a Heavy Duty Diesel Truck Costing About $30,000.[G3]

Table G.1-1

Summary of Increased Operating Costs for Heavy Trucks Resulting from Modifications to Achieve Reduced Noise Emission

Level of Noise Reduction Achieved (Re: SAE J366b)	Increased Operating Costs/Formulation*
80 dB	+ $75 per year in maintenance to remove partial engine enclosure for service.
75 dB	+ $365 per year in maintenance to remove full engine enclosure for service. Loss in payload capacity resulting from ≈ 400 pound full engine enclosure = 0.0675 x (ΔGVW) = 0.0675 (400 pounds) = $27 per year. Reduced performance due to increased back pressure in exhaust system = $7 per year per inch H_2O increase in pressure.**

*Source: Reference A5.

**Section 6.2.3 discusses the advantage of using a demand-type fan clutch. The gain due to its use would probably at least balance the losses due to increased back pressure.

First we list the general assumptions covering all analysis cases, with specific assumptions being considered under the treatment of each case.

Assumptions

a. Annual rate of growth in Spokane heavy truck fleet is 4.4 percent. This figure is based upon a compilation of new truck registration statistics indicating a 10.7 percent rate and annual scrapping rate of 6.3 percent for the United States from 1955 to present. Source: Reference A4.

b. Useful life of a heavy truck: 16 years.

c. Average useful life remaining of existing fleet (for retrofit analysis): 8 years.

d. Increased operating costs due to emission of reduced noise levels: Table G.1-1.

e. Range of increased acquisition costs due to noise reduction: Figure G.1-1. (Note that for the analysis year, 1978, no new production nor retrofit below the level of 80 dB (SAE J366b) is considered technically nor economically feasible.)

Analysis:

Determine discounted number of future units:

$$\begin{pmatrix}\text{Number of New 1973 Units}\\ \text{Charged to Spokane}\end{pmatrix} = \begin{pmatrix}\text{Total 1973 Fleet}\\ \text{Charged to Spokane}\end{pmatrix} \times \begin{pmatrix}\text{Average Annual}\\ \text{New Vehicle}\\ \text{Registration Rate}\end{pmatrix}$$

$$= (886) \times (10.7 \text{ percent}) = 94.8 \qquad \text{(G-2)}$$

10 percent Discounted Growth Factor at +4.4 percent overall annual growth rate – from Figure 7.2-1: 18.3 (see discussion at beginning of Section 7.2).

Thus: Discounted number of future units = (18.3) (94.8) = 1735.

Now, considering the various new production/retrofit scenarios individually, we treat first the new manufacturing costs with any associated increased operational expenses and, secondly, the retrofit analysis in Section G.2.

Case 1 New production at 86 dB (SAE J366b) (current production levels) through 1973, no retrofit of existing fleet.

Analysis: No increased costs associated with this case.

Case 2 New production at 86 dB (SAE J366b) through 1978 (no cost – Re: Case 1) and retrofit of existing fleet to 86 dB.

Case 3 New production at 86 dB (SAE J366b) for 1974 and 1975 (no cost – Re: Case 1), followed by new production at 83 dB for 1976 through 1978. Retrofit existing fleet to 86 dB.

Analysis: To determine the discounted number of new production units which incur additional costs due to reduced noise emission, we take the total discounted number of future units and subtract the discounted number of 1974 and 1975 units (Re: Figure 7.2-2):

Discounted number of future units: 1735 – 89.9 – 85.2 = 1560

Range of increased acquisition costs (Re: Figure G.1-1):
$300 to $600/unit

Range of present value of increased acquisition costs:
($300 to $600) (1560) = $468,000 to $936,000

No increased operating costs are anticipated for this level of reduction.

Case 4 New production at 83 dB (SAE J366b) through 1978, retrofit existing fleet to 86 dB.

Analysis: Range of increased acquisition costs (Re: Figure G.1-1):
$300 to $600/unit (no increased operating costs)

Thus, range of present value of increased acquisition costs:
($300 to $600) (1735) = $520,500 to $1,041,000

Case 5 New production at 83 dB (SAE J366b) through 1978, retrofit existing fleet to 83 dB.

Analysis: Range of increased acquisition costs as in Case 4:

$520,500 to $1,041,000

Case 6 New production at 83 dB (SAE J366b) for 1974 and 1975, followed by new production at 80 dB through 1978. Retrofit existing fleet to 83 dB.

Analysis:

a. Range of costs for production at 83 dB: $300 to $600

Discounted number of 1974 and 1975 units (Ref. Case 3): 89.9 + 85.2 = 175

Range of increased acquisition costs for 1974 and 1975 units:

($300 to $600) (175) = $52,500 to $105,000

No increased operating costs at this level.

b. Range of costs for production at 80 dB (Re: Figure G.1-1): $450 to $900

Discounted number of 1976 units and thereafter (Ref. Case 3): 1560

Range of increased acquisition costs for 1976 units and thereafter.

($450 to $900) (1560) = $702,000 to $1,404,000.

c. Increased operating costs for 80 dB trucks (Re: Table G.1-1): $75/year

Thus:

$$\begin{pmatrix}\text{Present Value of Increased}\\ \text{Operating Costs Over}\\ \text{16 Year Life Per Unit}\end{pmatrix} = 75 \times \begin{pmatrix}\text{Present Value}\\ i = 10\text{ percent}\\ n = 16\text{ years}\end{pmatrix} = 75 \times 7.824 = \$587 \qquad \text{(G-3)}$$

Thus, the total present value of increased operating costs for all 80 dB trucks = ($587/truck) (1560: Discounted number of future units) = $916,000.

Case 7 New production at 83 dB (SAE J366b) for 1974 and 1975, followed by new production at 80 dB through 1978. Retrofit 1974 and 1975 units and existing fleet to 80 dB by 1978.

Analysis: Present value of increased acquisition costs of new production units as in Case 6:

a. Production of 83 dB trucks in 1974 and 1975: $52,500 to $105,000

b. Production of 80 dB trucks from 1976 on: $702,000 to $1,404,000

c. Increased operating costs for 1976 units on: $916,000

The retrofit analysis for all cases follows.

G.2 NOISE REDUCTION RETROFIT ANALYSIS

Table G.2-1 presents an analysis of the Spokane heavy duty truck fleet through the 1978 time period.

Upon reaching the 83 to 80 dB range of required noise levels, the costs are very similar, since it is assumed that the same approaches would be pursued for both levels if done on a retrofit basis.

The total cost range for each plateau of noise level desired is derived by assuming the lowest figure on the quietest truck to achieve plateau and then the sum of all the possible component costs to quiet the loudest truck.

Retrofit means modifying and/or replacing components. These modifications are progressively more involved as the required noise level of the trucks is reduced. All of the modifications are assumed to modify the truck in a manner that would not void factory warranties. This would include compliance with cooling specifications, exhaust back pressures, and intake pressure drops.

There are no costs inserted for the testing and evaluation necessary to establish component noise reduction, nor are there any costs shown for compliance testing.

Figure G.2-1 illustrates the distribution of a range of SAE J366b noise emission levels for heavy trucks aged 2 years or less as compiled by the SAE Vehicle Sound Level Committee. Such distribution data is not available for older vehicles and the values shown are assumed. Thus, the cost of retrofitting the existing truck fleet to achieve various levels can then be derived as illustrated in Table G.2-4 by using the cost figures in Table G.2-3 and the assumed truck populations shown in Figure G.2-1.

Table G.2-1

Analysis of Spokane Heavy Truck Fleet Through 1978

Year	Number of Heavy Duty Trucks at Beginning of Year	Number Scrapped (6.3% Average Rate*)	Number Added (10.6% Average New Registrations*)	Total Fleet at Year End (4.3% Average Growth Rate*)
1973	886	56	95	925
1974	925	58	99	966
1975	966	61	103	1008
1976	1008	64	108	1053
1977	1053	66	112	1099
1978	1099			

*Based upon averaging of new vehicle registrations and annual scrappage statistics from 1955 to present – Source: Reference A4.

Of the 1099 heavy duty trucks charged to Spokane in 1978, 518 are new production units (since 1973) and 581 are pre-1973 potentially requiring noise reduction retrofit. We have chosen to categorize the heavy truck population according to vehicle age and hence, define their mean noise levels as a function of their age. Thus, one is then able to define the major components responsible for the resultant noise levels for specific segments of the vehicle fleet. This breakdown can be generated from various noise source identification programs completed on trucks and noise survey programs of in-service vehicles. The distribution of the heavy truck fleet according to age is shown in Table G.2-2.[U5]

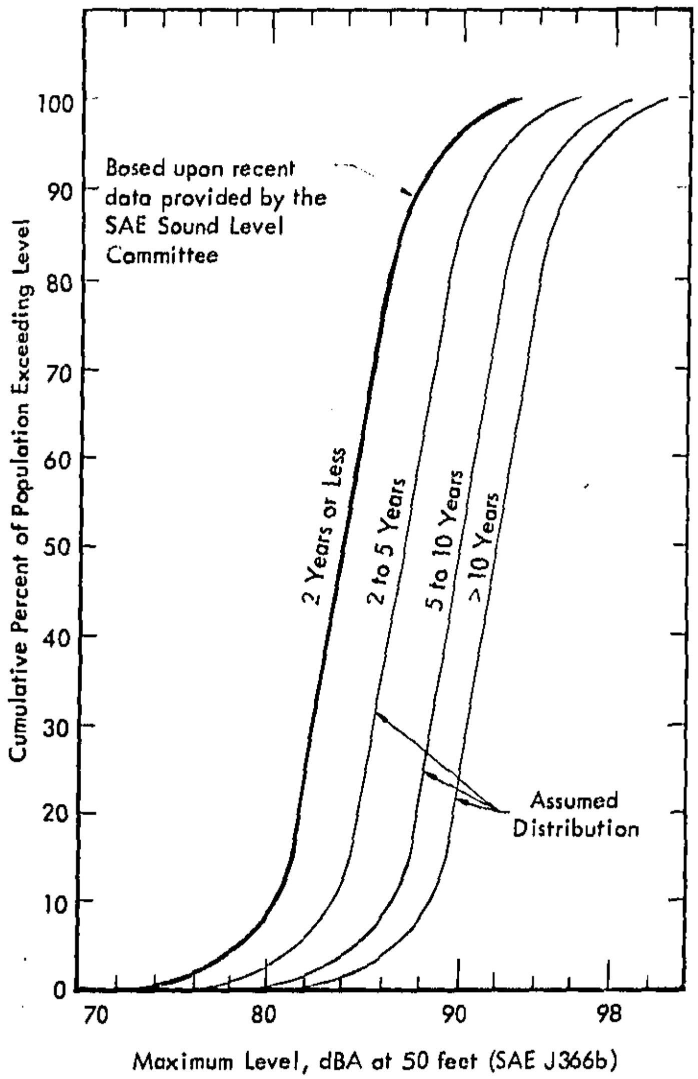

Figure G.2-1. Noise Population Distribution of Heavy Diesel Trucks.

Table G.2-2

Age Distribution of U.S. Heavy Truck Fleet (Reference U5)

Vehicle Age Group	Percent of Total	Number of Vehicles (Thousands)
Less than 2 Years	19.5	294
2 to 5 Years	42.3	636
5 to 10 Years	21.8	328
Greater than 10 Years	16.4	246
Totals	100.0	1,504

Table G.2-3 is a tabulation of the various costs associated with the noise reduction required for a truck of a particular noise level to meet a specified desired noise level (SAE J366b). These data have been projected from manufacturers who are working on retrofit programs and from some who have worked on retrofit programs. The cost figures at this point in time would seem to be reasonable and realistic based upon the present state-of-the-art. The percentage of trucks requiring revision must necessarily be estimated figures, but they still hold some validity. It has not been assumed that all trucks will need muffler replacements. As an example, one quickly approaches a noise level where the exhaust, cooling system, and engine mechanical noise may alternately assume the role of predominance within different models of trucks. The lower noise level trucks will require noise reduction of one or more major components, but not all, since the major noise sources will have been reduced in the manufacturing stage.

Table G.2-3

Estimated Cost to Retrofit Heavy Duty Trucks
(References A5, C5, F4, G2, P3, and W5 Have Been Used for Cost Data and for Determining Required Component Changes, References J2, S7, S8, and T1 Only for the Latter)

Noise Level to be Achieved* dB	Existing Noise Level of Truck* dB	Required Treatment	Estimated Cost Per Item $	Percent of Trucks Exceeding Specification Noise Level and Requiring Components	Estimated Range of Costs to Retrofit In-Service Vehicles $
90	92	Exhaust[1]	50-100	100	50-100
				Total Range	50-100
88	92	Exhaust[1]	50-100	100	50-100
	90	Exhaust[2]	50-100	90	50-100
				Total Range	50-100
86	92	Exhaust[3]	100	100	100-450
		Cooling System[4]	130-200	75	
		Engine[5]	80-150	25	
	90	Exhaust[2]	50-100	100	50-450
		Cooling System[4]	130-200	75	
		Engine[5]	80-150	10	
	88	Exhaust[2]	50-100	50	50-300
		Cooling System[4]	130-200	50	
				Total Range	50-450
83	92	Exhaust[6]	100-150	100	385-865
		Cooling System[7]	285-400	100	
		Engine[8]	100-200	50	
		Intake[9]	115	30	
	90	Exhaust[6]	100-150	100	385-865
		Cooling System[7]	285-400	100	
		Engine[8]	100-200	50	
		Intake[9]	115	25	
	88	Exhaust[6]	100-150	75	200-865
		Cooling System[7]	285-400	75	
		Engine[8]	100-200	50	
		Intake[9]	115	20	
	86	Exhaust[6]	100-150	50	100-865
		Cooling System[7]	285-400	50	
		Engine[8]	100-200	50	
		Intake[9]	115	10	
				Total Range	100-865

Table G.2-3 (Continued)

Noise Level to be Achieved* dB	Existing Noise Level of Truck* dB	Required Treatment	Estimated Cost Per Item $	Percent of Trucks Exceeding Specification Noise Level and Requiring Components	Estimated Range of Costs to Retrofit In-Service Vehicles $
80	92	Exhaust[6]	100-150	100	600-865
		Cooling System[7]	285-400	100	
		Engine[8]	100-200	100	
		Intake[9]	115	100	
	90	Exhaust[6]	100-150	100	485-865
		Cooling System[7]	285-400	100	
		Engine[8]	100-200	100	
		Intake[9]	115	75	
	88	Exhaust[6]	100-150	100	485-865
		Cooling System[7]	285-400	100	
		Engine[8]	100-200	100	
		Intake[9]	115	50	
	86	Exhaust[6]	100-150	50	385-865
		Cooling System[7]	285-400	100	
		Engine[8]	100-200	50	
		Intake[9]	115	25	
	83	Exhaust[6]	100-150	25	100-865
		Cooling System[7]	285-400	50	
		Engine[8]	100-200	100	
		Intake[9]	115	10	
				Total Range	100-865

[1]Muffler and labor.

[2]Muffler and labor.

[3]Muffler, new exhaust tubing and labor.

[4]Revision of cooling system: install radiator recirculation shields, new shroud, new fan, fan pulley, and labor.

[5]Engine panels and labor.

[6]Muffler (double wall), resonator chambers, exhaust stacks, replacement of exhaust flex tubing with ballpoint connectors and labor.

[7]Temperature-sensitive fan clutch and fan radiator recirculation shields, new shroud or rework as in Number 4, and labor.

[8]Engine panels, rear panel enclosure for cab and labor.

[9]Tuned intake with integral suppressor and labor.

*As determined by SAE J366b (at 50 feet)

Table G.2-4

Range of Retrofit Costs to Achieve Given Noise Levels

(J366b) Desired Noise Level dB	Age	Number of Trucks at Given Levels (Thousands) dB: Number	Range of Costs Per Truck $	Range of Total Costs $
86	10 yrs +	92+: 132	100-450	13,200-59,400
		90-92: 103	100-450	10,300-46,350
		88-90: 41	50-450	2,050-18,450
		86-88: 9	50-300	450- 2,700
	5-10 yrs	92+: 127	100-450	12,700-57,150
		90-92: 191	100-450	19,100-85,950
		88-90: 191	50-450	9,550-85,950
		86-88: 89	50-300	4,450-26,700
	2-5 yrs	92+: 23	100-450	2,300-10,350
		90-92: 26	100-450	2,600-11,700
		88-90: 66	50-450	3,300-29,700
		86-88: 98	50-300	4,900-29,400
	<2 yrs	92+: 2	100-450	200- 900
		90-92: 7	100-450	700- 3,150
		88-90: 10	50-450	500- 4,500
		86-88: 34	50-300	1,700-10,200
Total				88,000-482,550

Average Cost Per Vehicle: $77 to $420

Table G.2-4 (Continued)

(J366b) Desired Noise Level dB	Age	Number of Trucks at Given Levels (Thousands) dB: Number	Range of Costs Per Truck $	Range of Total Costs $
83	10 yrs +	92+: 132	385-865	50,820-114,180
		90-92: 103	385-865	39,655- 89,095
		88-90: 41	385-865	15,785- 35,465
		86-88: 9	200-865	1,800- 7,785
		83-86: 9	100-865	900- 7,785
	5-10 yrs	92+: 127	385-865	18,895-109,855
		90-92: 191	385-865	73,535-165,215
		88-90: 191	385-865	73,535-165,215
		86-88: 89	200-865	17,800- 76,985
		83-86: 25	100-865	2,500- 21,625
	2-5 yrs	92+: 23	385-865	8,855- 19,895
		90-92: 26	385-865	10,010- 22,490
		88-90: 66	385-865	25,410- 57,090
		86-88: 98	200-865	19,600- 84,770
		83-86: 98	100-865	9,800- 84,770
	<2 yrs	92+: 2	385-865	700- 1,730
		90-92: 7	385-865	2,695- 6,055
		88-90: 10	385-865	3,850- 8,650
		86-88: 34	200-865	6,800- 29,410
		83-86: 111	100-865	11,100- 96,015
Total				424,115-1,204,080

Average Cost Per Vehicle: $305 to $865

Table G.2-4 (Concluded)

(J366b) Desired Noise Level dB	Age	Number of Trucks at Given Levels (Thousands) dB: Number	Range of Costs Per Truck $	Range of Total Costs $
80	10 yrs +	92+: 132	600-865	79,200-114,180
		90-92: 103	600-865	61,800- 89,095
		88-90: 41	485-865	19,885- 35,465
		86-88: 9	485-865	4,365- 7,785
		83-86: 9	385-865	3,465- 7,785
	5-10 yrs	92+: 127	600-865	76,200-109,855
		90-92: 191	600-865	114,600-165,215
		88-90: 191	485-865	92,635-165,215
		86-88: 89	485-865	43,165- 76,985
		83-86: 25	385-865	9,625- 21,625
		80-83: 13	100-400	1,300- 5,200
	2-5 yrs	92+: 23	600-865	13,800- 19,895
		90-92: 26	600-685	15,600- 22,490
		88-90: 66	485-865	32,010- 57,090
		86-88: 98	485-865	47,530- 84,770
		83-86: 98	385-865	37,730- 84,770
		80-83: 10	100-400	1,000- 4,000
	<2 yrs	92+: 2	600-865	1,200- 1,730
		90-92: 7	600-865	4,200- 6,055
		88-90: 10	485-865	4,850- 8,650
		86-88: 34	485-865	16,490- 29,410
		83-86: 111	385-865	42,735- 96,015
		80-83: 62	100-400	6,200- 24,800
Total				729,585-1,238,080

Average Cost Per Vehicle: $494 to $865

Table G.2-5

Summary of Average Range of Costs Per Unit to Retrofit the Existing Heavy Truck Fleet to Specified Levels of Noise Emission

Noise Level Achieved Through Retrofit (Re: SAE J366b), dB	Average Range of Costs Per Truck
86	$ 77 to $420
83	$305 to $865
80	$494 to $865

Table G.2-5 summarizes the results of Table G.2-4 for costs of noise reduction retrofit to the existing fleet to achieve defined noise levels as shown.

Hence, to achieve the overall fleet noise reductions as indicated in Cases 2 through 7, Figure 6.2-1, we wish to retrofit 116 units per year over 5 years to yield treatment of the total existing fleet in the 1978 time period of 581 units. Thus, to assess retrofit costs, we must first arrive at the discounted number of units treated over the 5-year compliance period as presented in Table G.2-6.

Table G.2-6

Determination of Discounted Number of Heavy Trucks for Retrofit Analysis

Year	Number of Vehicles Retrofitted	PV Discount Factor at 10%	Discounted Number of Units Treated
1973	116	1.0	116
1974	116	0.909	105.4
1975	116	0.826	95.8
1976	116	0.751	87.1
1977	116	0.683	79.2
1978	0		
Totals	580	4.17	483.5

Thus, the present value of all retrofit costs (excluding any increased operating costs) to achieve a specific noise level reduction for the fleet will equal the average cost to retrofit a single unit to the specified noise level multiplied by the "discounted number of units treated" (483.5).

The assignable retrofit costs for the 1978 Spokane, Washington analysis are summarized below:

Cases 2, 3, and 4: Retrofit to 86 dB (SAE J366b). Estimated range of costs/vehicle to achieve 86 dB (Table G.2-5) = $77 to $420/vehicle x 483.5 (Discounted Number of Units Treated) = $37,200 to $203,000.

Cases 5 and 6: Retrofit to 83 dB (SAE J366b). Estimated range of costs/vehicle to achieve 83 dB (Table G.2-5) = $305 to $865/vehicle x 483.5 = $147,500 to $418,200.

Case 7: Retrofit existing fleet to 80 dB and retrofit 1975 and 1975 production from 83 to 80 dB. As shown in Section 7.4.2 for automobiles, the total costs are also calculated with the retrofit hardware costs tripled for the retrofit labor cost sensitivity substudy (indicated by brackets ([ ])).

a. Existing fleet to 80 dB at \$494 to \$865/vehicle x 483.5 = \$238,900 to \$418,200 [716,700 to 1,254,600].

Increased operating cost: \$75/year x (5.335) = \$400/vehicle
Therefore: PV (OC) = \$400/vehicle x 483.5 = \$193,400.

b. Retrofit 1974 and 1975 production from 83 to 80 dB: 99 units produced in 1974 - require retrofit in 1977; 103 units produced in 1975 - require retrofit in 1978; thus, from 1973, the 1974 units need be treated in 4 years (hence, discount factor of 0.7513), and the 1975 units will be treated in 5 years (discount factor of 0.683). Thus, the discounted number of these units to be treated = 99 x 0.7513 + 103 x 0.683 = 144.7. The average cost/unit to retrofit from 83 to 80 dB = \$100 to \$400/unit x 144.7 = \$14,500 to \$57,900 [43,500 to 173,700].

Costs of operation of retrofitted 80 dB units are assumed identical to the 80 dB production units (see Section G.1, Case 6, item c). Hence, (144.7 units) (\$587/Unit) = \$85,000.

Thus, the range of present value of total cost for each analysis case consists of the sum of increased acquisition cost plus increased operating costs for retrofitted units. These costs are summarized in Table G.2-7 and resultant noise reduction (re: the analysis conducted in Section 6.2) versus cost function for low-speed heavy trucks is given in Figure G.2-2.

Table G.2-7

Summary of Present Value of Total Costs to Achieve Heavy Truck Noise Reduction Scenario Cases 1 Through 7[1] [Case of Tripled Retrofit Hardware Costs in Brackets]

Noise Reduction Scenario (Noise Levels re:SAE J366b)	Resultant Low Speed Noise Reduction, dB (re: Section 6.2)	Range of Present Value of Costs to Achieve Noise Reduction Scenario, in Millions of 1973 Dollars[2]				
		Increased New Acquisition	Increased Operation - New Units	Retrofit Existing Fleet	Increased Operation - Retrofitted Units	Total
Case 1. Continue production at 86 dB - no retrofit	2.7	0	0	0	0	0
Case 2. Continue production at 86 dB - retrofit to 86 dB	4.7	0	0	0.04 to 0.20	0	0.04 to 0.20
Case 3. 1974 and 1975 production at 86 dB, 1976 + production at 83 dB - retrofit to 86 dB	5.3	0.47 to 0.94	0	0.04 to 0.20		0.51 to 1.14
Case 4. New production at 83 dB - retrofit to 86 dB	5.8	0.52 to 1.04	0	0.04 to 0.20	0	0.56 to 1.24
Case 5. New production at 83 dB - retrofit to 83 dB	7.7	0.52 to 1.04	0	0.15 to 0.42	0	0.67 to 1.46
Case 6. 1974 and 1975 production at 83 dB, 1976 + production at 80 dB - retrofit to 83 dB	8.3	0.75 to 1.51	0.92	0.15 to 0.42	0	1.82 to 2.85
Case 7. 1974 and 1975 production at 83 dB, 1976 + production at 80 dB - retrofit 1974 & 1975 and existing fleet to 80 dB	10.7	0.75 to 1.51	0.92	0.26 to 0.476 [0.76 to 1.43]	0.27	2.2 to 3.17 [2.7 to 4.13]

(1) Scenarios defined in Figure 6.2-1.

(2) Costs for only the truck population assigned to Spokane, Washington.

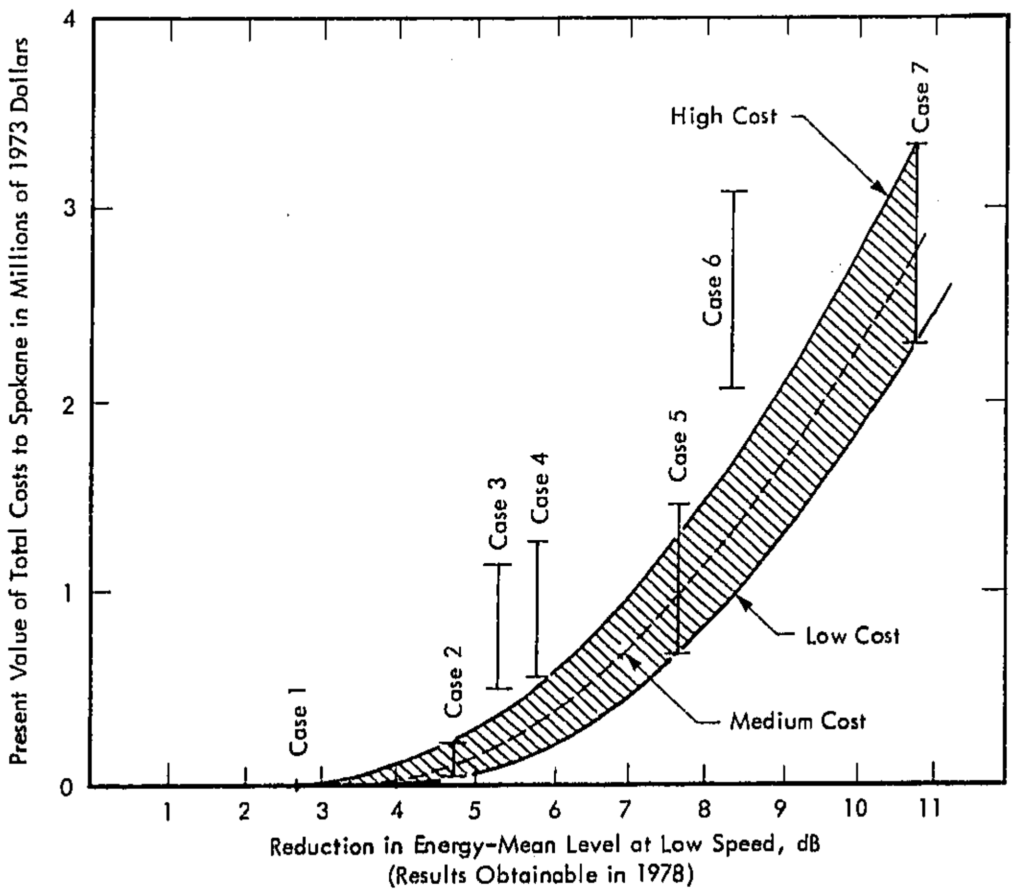

Figure G.2-2. Present Value of Heavy Truck Noise Reduction Costs [Case of Tripled Retrofit Hardware Costs: Multiply Cost Functions by 1.3 (= (4.13 + 2.7)/ (2.2 + 3.17), from Case 7, Table G.2-7)]

G.3 HIGH SPEED NOISE REDUCTION

We define high speed as greater than 35 mph. As mentioned in Section 6.2, the dominant noise source for the majority of heavy trucks at these speeds is tire noise. By replacing crossbar-design tires with rib-design tires, a reduction of the order of 5 dB can be achieved.[T3] The associated economic penalty is rather severe as the analysis below will show. The economically more attractive solution of retreading rib tires to gain additional life at nominal cost (~ $30) is not satisfactory because many trucking companies prefer for safety reasons that at least half of the drive tires not be retreaded.

The sequel presents an analysis of the costs to eliminate crossbar tires from the driving axles. The costs are expressed simply as increased operating costs over the life of the truck. First, the relative new costs and expected life of two crossbar designs are considered versus the quiet rib design as shown in Table G.3-1.[R5]

Table G.3-1

Relative Costs of Heavy Truck Drive Tire Tread Designs

Tire Tread Design	New	Life	Cost/Mile	Cost/Year at 35,000 Miles Per Year
Rib	$130	50,000	$0.0026	$91.00
Rayon-Crossbar	$143	70,000	$0.00204	$71.50
Steel Radial-Crossbar	$200	100-130,000 (use 115,000)	$0.00174	$60.87

<u>Assumptions Governing Analysis:</u>

Average annual mileage: 35,000 miles/year (average heavy duty truck) (Source: Reference U5, Figure 7).

Thus, we may compute the expected life of each tire design:

$$\text{Rib: } \frac{50}{35} = 1.43 \text{ years}$$

$$\text{Rayon Crossbar: } \frac{70}{35} = 2 \text{ years}$$

$$\text{Steel Radial-Crossbar: } \frac{115}{35} = 3.29 \text{ years}$$

Next, we wish to compute the expected number of tire changes per year as follows:

$$\text{Number of changes} = \frac{1}{\text{life}}$$

Thus:

Rib: 1/1.43 = 0.7

Rayon Crossbar: 1/2 = 0.5

Steel Radial Crossbar: 1/3.29 = 0.3

And, the tire change cost/year per tire at a $12/hour labor rate with a single tire change requiring 0.5 hours; thus, 0.5 x $12 = $6/change

Rib: 0.7 x $6 = $4.20

Rayon Crossbar: 0.5 x $6 = $3.00

Steel Radial Crossbar: 0.3 x $6 = $1.80

Combining the above-determined costs yields the total operating cost per year per heavy truck:

		Increased Cost with Respect to Rib, per Tire
Rib:	$91.00 + $4.20 = $95.20	0
Rayon Crossbar:	$71.50 + $3.00 = $74.50	+$20.70
Steel Radial Crossbar:	$60.87 + $1.80 = $62.67	+$32.53

Finally, we assume that each truck is "charged" for 6 drive tires. These tires must be new - not retreaded; therefore retread economics will not be considered in this analysis. The range of increased operating costs per heavy duty truck resulting from restrictions on crossbar-design tires on the driving axles is computed below:

6 tires/truck x \$20.70 to \$32.53 = \$124.20 to \$195.18

The present value of these costs per truck over the truck's total useful life of 16 years may be determined by multiplying the annual range of costs by the present value factor defined as follows:

$$\begin{pmatrix} \text{Present Value} \\ i = 10 \text{ percent} \\ n = 16 \text{ years} \end{pmatrix} = \frac{(1+i)^n - 1}{i(1+i)^n} = 7.824 \qquad \text{(G-4)}$$

Thus, the present value per truck = (7.824)(\$124.20 to \$195.18) = \$972 to \$1527/vehicle.

Finally, using the total number (1735) of discounted future heavy trucks in the Spokane fleet from the previous analysis in Section 7.5.1, we may arrive at the total assignable costs for crossbar tire restrictions:

(\$972 to \$1527/vehicle)(1735) = \$1.7 to \$2.7 million 1973 dollars.

It should be pointed out that retrofit of trucks with quieter tires is assumed to be accomplished on a phased schedule at the time normal tire replacement is required.