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REPORT

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WYLE RESEARCH REPORT

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NATIONAL EXPOSURE TO HIGHWAY NOISE THROUGH THE YEAR 2000

For

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Noise Abatement and Control
Arlington, Virginia 22202

Contract No. 68-01-3514

By

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Arlington, Virginia 22202

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REPORT

FOREWORD

In obtaining a copy of this report, it is reasonable for us to assume that you, the reader, have an interest in noise abatement and control. It is also reasonable for us to assume that you expect to learn something of the extent and nature of the noise problem in America and what, if any thing can be done about it. With these assumptions in mind, we thought it would be beneficial to state at the outset what we intended for you to derive out of this report and others of this type we plan to publish in the future.

The major purpose of this study was to identify future technology requirements for source noise control of highway vehicles. Obviously, the results of any study dealing with the future are highly dependent on the assumptions we make about the future. The following are among the more important factors to be considered:

- The number and types of vehicles
- Vehicle operations and resulting noise characteristics
- The effectiveness of use and operational controls to reduce noise (which in turn are dependent upon the willingness of the user to employ such means and of the state and local governments to exercise their authorities to achieve compliance)
- The application of other effective means of mitigating the adverse consequences of the public's exposure to excessive noise (such as compatible land use and the use of barriers).

These latter techniques, although not controlling noise at the source, may have a significant effect on the extent of the source control applications because they can be implemented in relatively shorter time periods, and the noise reductions are additive to whatever reductions can be achieved through source control technology.

Because of the uncertainties associated with precisely predicting the future, the sensitivity of the findings to the assumptions employed was examined. It is the Environmental Protection Agency's intention to develop a series of these "future technology" studies, covering other noise sources. We are hopeful that those charged with the problem of developing noise control technology will find some guidance for their programs from these reports.

John C. Schettino, Director
Technology and Federal Programs Division
Office of Noise Abatement and Control
Environmental Protection Agency
Washington, D.C.

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I would also like to thank the following members of the Wyle Research Staff for their contributions to this project: Dr. Ben H. Sharp for many helpful discussions; Mr. John Moran for developing the software package; Mr. Patrick Glenn for his invaluable assistance in demographic data collection and the selection of sample cities; Mr. Vijay Kohli for performing the barrier calculations in Appendix A; Dr. Paul Donavan for providing the stop/go adjustment in Appendix C; and Messers Don Pies and R. G. Kunicki for their assistance in transforming census and traffic maps into data files.

We would also like to thank the following agencies for providing local traffic information:

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Chicago Department of Traffic Engineering
Milwaukee Department of Traffic Engineering Administration

Metric Conversions

Much of the source data used in this study, obtained from regional and federal government agencies, was available only in English units. To permit this study to be directly keyed to these source data, calculations were performed without conversion to metric units. All major results are presented in metric and English units, however, as are common quantities such as speed and distance. Use of dual notation in the entire text would have been awkward, so that some intermediate calculations are presented in English units only. The following conversion factors may be used to convert these to metric units:

1 foot	=	0.305 meters (m)
1 mile	=	1.609 kilometers (km)
1 square mile	=	2.589 square km
1 pound (mass)	=	0.454 kilograms (kg)

1.0 INTRODUCTION

The noise from highway traffic is a major noise source dominating most outdoor noise environments. The overall noise is made up of contributions from individual vehicles within the traffic flow, so that a fundamental approach to reducing highway noise exposure on a national scale consists of modifying the noise produced by these vehicles. This noise can be reduced by the imposition of noise standards to new vehicles, to existing vehicles, by modifying vehicle operation, or by a combination of all three. An optimum strategy can be defined by evaluating the effectiveness of different scenarios containing one or more of these methods. In this study, the nationwide exposure to highway noise is computed through the year 2000 and the effectiveness of various options for reducing this exposure is evaluated. The results of this study will help to define future research and development requirements in vehicle noise control.

A key feature of the present study is that growth of motor vehicle usage and population is included in the exposure calculation for future years. The baseline case of no changes in vehicle levels exhibits growth in exposure with time. This permits an evaluation of noise control options with respect to absolute changes in exposure as well as relative comparisons. Inclusion of growth also places perspective on the importance of timing for potential strategies which cannot be implemented immediately or whose effectiveness takes time.

The evaluation of vehicle noise abatement options can be divided into two parts. First, the noise exposure is computed as a function of the individual vehicle noise levels. The goals of exposure reduction can then be restated as goals of vehicle noise reduction. The second part is the evaluation of options, or combinations of options, in achieving these vehicle noise reduction goals. One alternative depends upon regulatory actions which are stated in terms of some limitation on vehicle operation or design. The direct effect of a regulation is to change the statistical distribution of the noise levels of vehicles operating on the highway. The change in the average noise level can be calculated on the basis of the change to the distribution. For a given scenario, this change is generally time dependent. The kinds of regulations and the required noise control technology needed to achieve desired abatement goals may then be determined.

The basic options considered in this study are those related to vehicle source control, because these provide benefits wherever the vehicle operates. A comprehensive national strategy should also include applications of local measures such as traffic management and barriers. These measures are implemented to provide abatement to areas which are exposed to noise significantly above the national average. Appendix A contains an analysis of the potential national benefit of one local measure, barriers. The two approaches supplement each other, in that vehicle controls reduce national average exposure, while local measures mitigate worst cases relative to average. Because of this supplementary relation, it is not reasonable to consider trade-offs between the two.

Most of the elements required for this study are already established. Reference 1 provides both a highway noise model which clearly defines the relation between highway and vehicle levels, and a model for computing the change to average vehicle level as a function of noise abatement scenarios. These two models are reviewed briefly in Sections 1.1 and 1.2. For the present study, the highway noise model is modified and combined with population information to give community exposure in the present and the future. The calculation approach, discussion of assumptions and data used, and calculations for several baseline scenarios, are presented in Section 2.0. A discussion of vehicle noise goals required to achieve given exposure reductions is contained in Section 3.0.

Although the computational elements required for this study were already established, it was necessary to develop new computer programs to perform the calculations. Because of the nature of the calculations, the final computational package consisted of a system of several programs. The function of each program, and their interrelationships, are discussed in Appendix B.

1.1 Highway Noise as a Function of Vehicle Noise Level

When a single vehicle moves along a highway, the resulting noise level at a receiver location near the highway is a function of the vehicle noise characteristics, time and the distance of the receiver from the vehicle. The most common representation of the noise level produced by a single vehicle is the maximum A-weighted sound pressure level* observed as the vehicle passes a microphone at a reference distance of 50 feet (15 meters). To compute the time history, it is generally assumed that source characteristics are omnidirectional — a reasonable assumption for many vehicles (see directional data in Reference 2, for example). Even for vehicles with non-symmetric source patterns, where the maximum level does not correspond to the vehicle being nearest the measurement point, a symmetric effective source can often be assumed with respect to the time of maximum level.[3]

For traffic flow with many vehicles, the noise level at a given time is the combination of instantaneous levels from all vehicles. To compute the energy-equivalent noise level, L_{eq}, the noise contribution from each vehicle is expressed in terms of its energy-average value and then summed over all vehicles. It is shown in Reference 1 that the value of L_{eq} at a distance d for a single lane of vehicles with pass-by level L is:

$$L_{eq} = L + 10 \log_{10} \frac{\pi d_o^2 Q}{Vd} \qquad (1)$$

where d_o is the distance at which the reference vehicle noise level L is measured, Q is the number of vehicles passing per unit time, and V is the vehicle speed. Propagation losses, other than geometrical spreading, are not included in this expression.

Real traffic contains a variety of vehicles with different pass-by levels. Figure 1 shows a typical statistical distribution of truck noise levels obtained from roadside measurements at 50 feet.[4] To account for the distribution of vehicle noise level, the quantity L in Equation (1) is replaced by the energy-average noise level of the distribution, denoted by L^{eq}.** This formulation also permits several vehicle classes to be handled, as shown in Section 2.2.1.

The modeling of highway noise must also include propagation losses, speed variations and different lanes or separate roads. Incorporating propagation loss in the form of power law excess attenuation,[1] the expression for L_{eq} for a single lane of vehicles travelling at a single speed becomes:

* All sound levels discussed in this report are A-weighted values in dB re: 20 μPA.

** In this study, L^{eq} represents the fleet energy-average of the maximum pass-by levels at 50 feet.

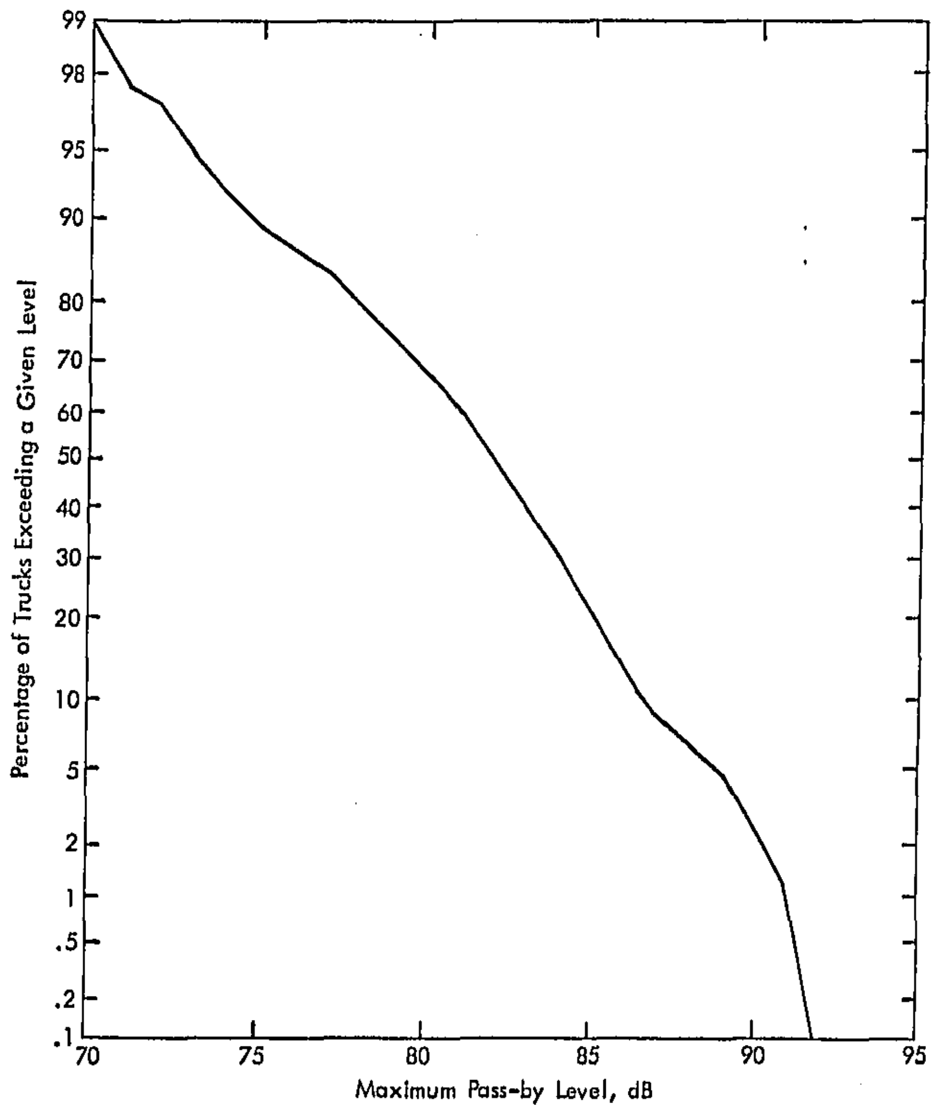

Figure 1. Noise Level Distribution of Trucks in Speed Zones Less Than 35 mph (56 kmh), Based on Data in Reference 4.

$$L_{eq} = L^{eq} + 10 \log_{10} \frac{\pi d_o Q}{V} + 10 K \log_{10} \frac{d_o}{d} - G(K) \qquad (2)$$

where K is a propagation constant with a value between 1 and 3, and G (K) is a function of K with a value between 0 and 3 dB. G (K) accounts for propagation losses from distant road elements, and is derived in Reference 1. For typical ground surfaces adjacent to highways (short grass, dirt), K = 1.5 and G (K) = 1.2 dB.

Cases of varying speeds, multiple lanes and multiple roads are handled by computing L_{eq} separately for each speed and lane, and then combining the levels. For the present purpose of calculating total highway noise exposure and evaluating source abatement options, Equation (2) contains the essentials of the noise prediction model. The most significant result indicated by Equation (2) is that the quantity L_{eq} is directly proportional to L^{eq}. The quantity L^{eq} is thus used to represent the average source strength of all vehicles at a given speed by means of a single number.

For an evaluation of noise exposure, the number of people exposed to various levels (L_{eq}, or L_{dn} if the day/night split is known) is calculated. If the traffic flow, road length and population density data are available, the number of people exposed to various levels can be determined by solving Equation (2) for d to give the distance to a given L_{eq} contour. The exposure may then be described as a statistical distribution of population vs. exposure level, as in Reference 5.

The formulation of this approach and the assumptions made are presented in Section 2.0. The relation between exposed population and L^{eq} is a one-to-one function, so that a calculation of exposure in a given year can be made for various changes to L^{eq}. The evaluation of options then requires only the calculation of L^{eq} as a function of time for a given source control scenario.

1.2 Vehicle Noise Level as a Function of Abatement Procedures

Motor vehicles on the highway have rather heterogeneous noise characteristics. Figure 1 illustrates this in a form related to the cumulative probability distribution for medium and heavy trucks at low speeds.[4] As noted above, the level corresponding to the average vehicle intensity weighted over the vehicle population is designated by L^{eq}. Mathematically this is written:

$$L^{eq} = 10 \log_{10} \left[\int p(L)\ 10^{L/10}\ dL \right] \qquad (3)$$

where p(L) is the vehicle population probability density function (infinitesimal fraction of vehicles exhibiting a level within the interval dL about L), normalized so that $\int p(L)\, dL = 1$. The quantity $p(L)\ 10^{L/10}$ is proportional to the distribution of acoustic energy among the vehicle population. Figure 2 shows the population and energy distributions for the same vehicles as Figure 1. The population distribution shows the fraction of vehicles exhibiting a particular level. The energy distribution shows the fraction of acoustic energy associated with vehicles at that level. The ratio between the two distributions is the acoustic energy per vehicle. Since the louder vehicles have proportionately greater contribution to L^{eq}, regulations should obviously be aimed initially at eliminating the noisy extreme of the population.

Two basic regulation types can accomplish this goal of eliminating the noisiest vehicles. These are:

- Operational limits, where existing vehicles would not be permitted to exceed certain pass-by levels. Vehicles below these levels would not be affected while those exceeding the limits would be brought into compliance by repair, retrofit, or elimination. An operating limit in principle eliminates the noisy end of the distribution in an ideal way. In practice, it is expected that repaired/retrofitted vehicles would be somewhat clustered just below the limit. Also, a certain degree of non-compliance must be expected. Figure 3 illustrates what the distribution of Figure 2 might look like after establishment of an operational limit of 88 dB.*
- New vehicle standards, where new vehicles would be required to meet noise standards. Figure 4 illustrates what the noise level distribution of new vehicles

* Specification of a noise limit carries some ambiguity due to variations between vehicles. If a specified limit is an absolute limit, then vehicle design must be aimed at a lower value. A second approach is to specify a limit to design to, and allow a reasonable tolerance for enforcement purposes. This second convention is adopted in the present study, so that Figure 3 shows some complying vehicles above the limit although the average level of retrofit vehicles is within compliance. The quantitative treatment of this convention is discussed in Section 3.3.1.

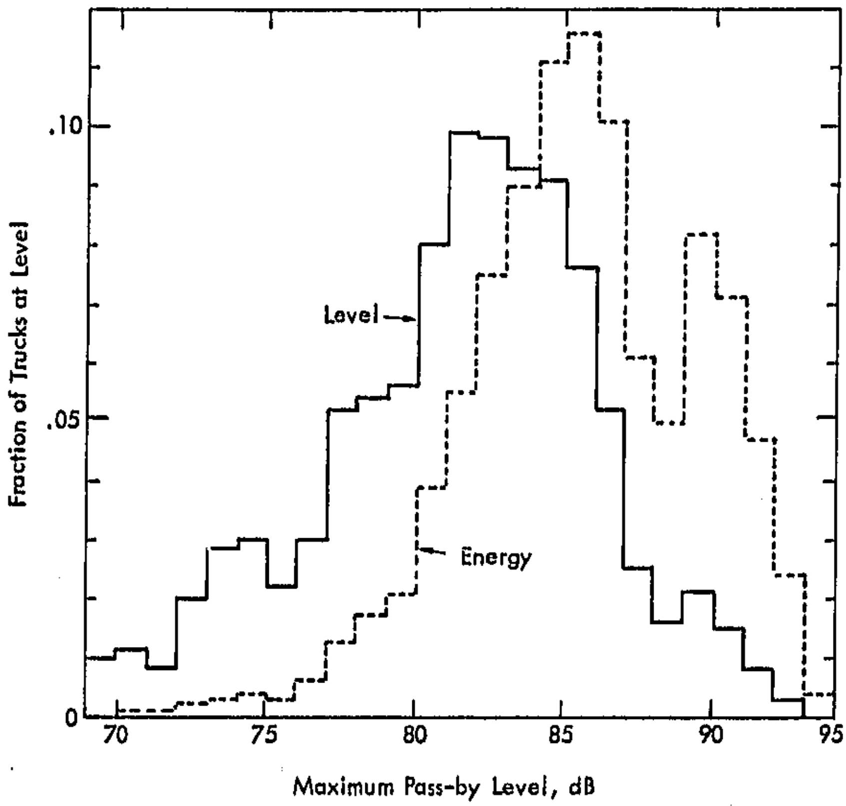

Figure 2. Noise Level and Energy Distributions of Trucks at Low Speeds (Based on the Noise Level Distribution Shown in Figure 1)

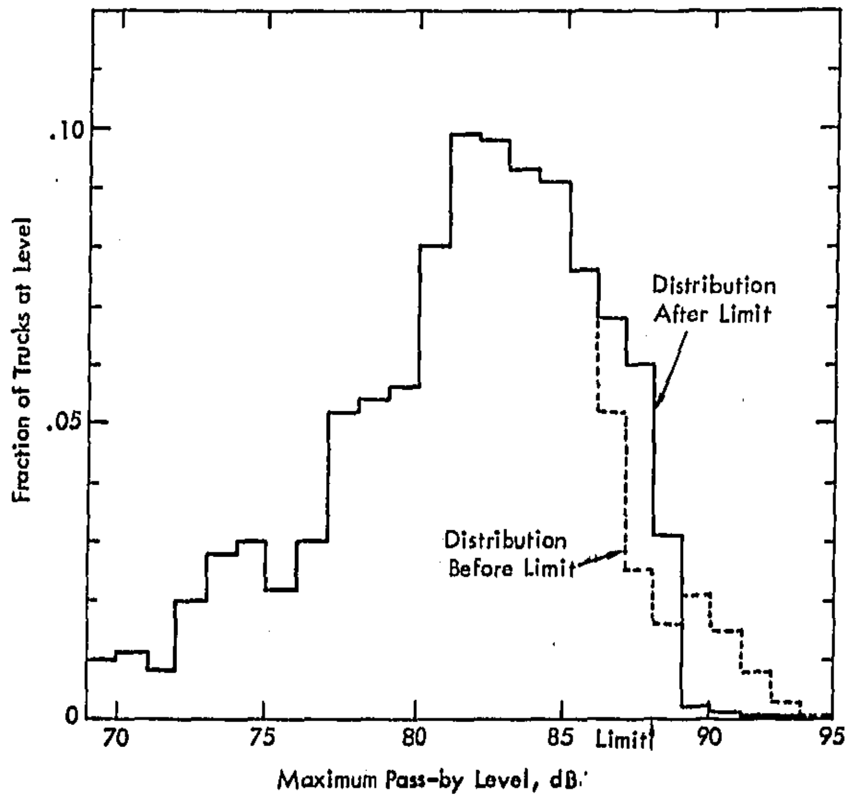

Figure 3. Effect of Operating Limit on Truck Noise Level Distribution

might be after the establishment of a new vehicle standard. Noisy vehicles manufacturerd before the standard would be eliminated from the total population by attrition over a period of years.

An effective control plan might consist of combinations of the two regulation types. The regulations could be applied in different years and periodically be made more stringent. For a given regulatory plan, the vehicle distribution changes yearly with a corresponding change to L^{eq}. A computer program (HINCSAM) is presented in Reference 1 which performs this calculation for any arbitrary scenario of these two regulation types. HINCSAM is used in Section 3.0 to evaluate various types of regulation scenarios.

A third type of abatement through regulations is the introduction of reduced speed limits. Vehicle noise levels generally increase with speed; reducing speed can therefore be applied as a local measure as well as a national regulation. Applied nationally, it would shift the entire noise distribution downward, affecting quiet vehicles as much as noisy ones. It is atractive, however, because no vehicle modifications are needed. Because it is a promising approach to local control, and its effect can be computed as an effective source reduction, a reduced urban truck speed limit (45 mph) is included in the scenarios considered in Section 2.7.

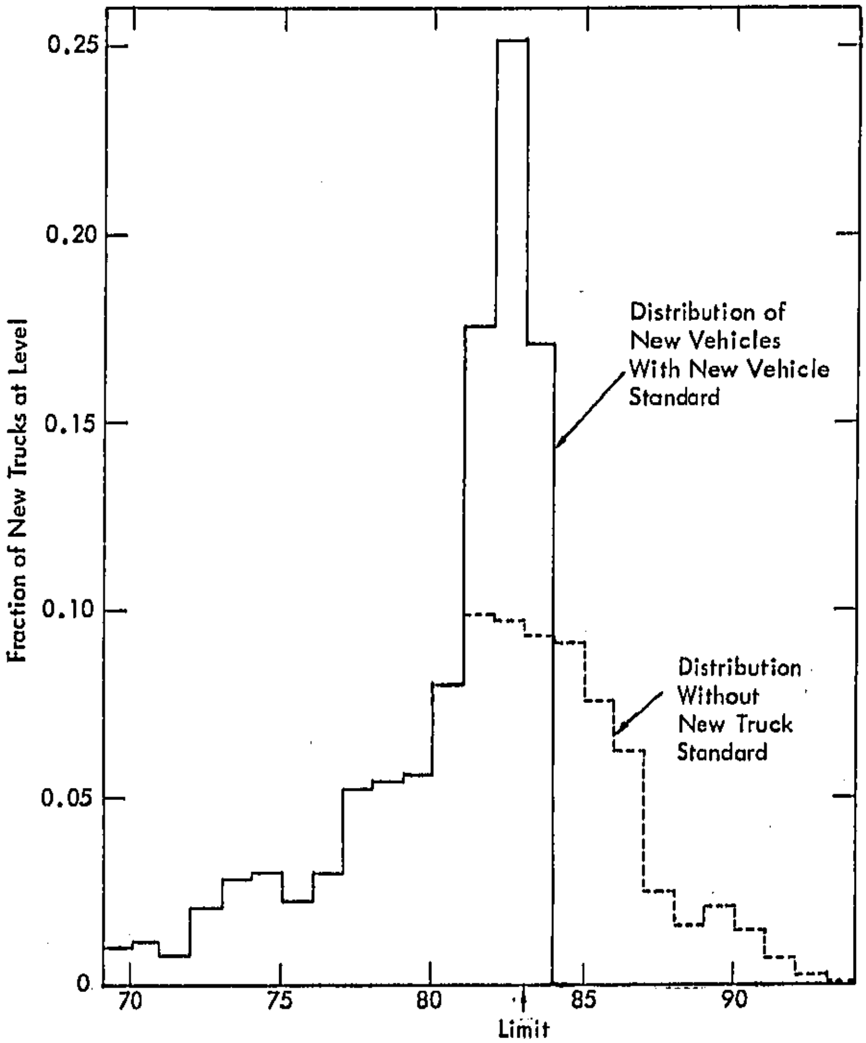

Figure 4. Effect of New Vehicle Standard on Distribution of New Truck Noise Levels at Low Speeds.

2.0 NATIONAL EXPOSURE TO HIGHWAY NOISE

2.1 Calculation Approach

Calculation of highway noise exposure in a given region requires the following steps:

- Gathering of traffic flow information for all roads in the region.
- Calculation of the distance from the road to various noise level contours, then multiplication by road segment lengths to obtain areas exposed.
- Gathering of population density data for the region.
- Cumulative summation of the product of exposed areas with population density to obtain the total number of people exposed.

For a specific city this procedure is straightforward. The computational model is described in Section 2.2. For the calculation of national exposure, it is not practical to compute noise for every street in the country. A statistical approach must be taken, with national exposure projected from calculations based on a representative sample of reliable local data. The approach taken in this study was to calculate actual exposure in a number of selected cities of various sizes, then apply fractions exposed to the total populations of all cities in those size categories. This represents a practical adaptation of a general approach based on obtaining joint distributions of traffic, highway mileage, and population for the entire nation. The distribution of U.S. population and the selection of cities are discussed in Section 2.3, together with projection to future years. The growth of vehicle use in the future is discussed in Section 2.4. Present and future vehicle noise levels are discussed in Section 2.5. Baseline noise exposure in urban and rural areas is presented in Section 2.6, and future noise exposure for several abatement scenarios is presented in Section 2.7.

2.2 Computational Model

2.2.1 Model Formulation

A calculation procedure has been developed to compute noise exposure in a given city. The noise calculation is based on Equation (2). The assumptions inherent in this model are:

- Freely flowing traffic except near traffic lights
- Simplified correction for stop-and-go traffic near lights
- Single-lane approximation
- Straight-road model

These approximations, except for the stop-and-go correction, are discussed in detail in References 1 and 3 and are reasonable for the present study. The stop-and-go model employed is discussed in Appendix C.

Equation (2) is solved for d to give distance to a given L_{eq} contour as a function of L^{eq}, propagation constant K, traffic volume, and speed. A computer program has been written which accepts this information together with population data for a city. The city is divided into tracts, areas over which population density are assumed constant. For each tract, the following data are required:

- Area of tract
- Population of tract
- Propagation constant, K
- Road and traffic information. The highway system is divided into elements for which traffic conditions are constant. For each element, the program requires:
  - Average daily traffic
  - Percentage of trucks
  - Traffic speed
  - Length of road
  - Number of traffic lights per mile

A city may be divided into any number of tracts. Roads within a tract may be divided into as many elements as necessary to describe accurately traffic conditions. In practice, road elements are defined in as much detail as available traffic flow maps provide.

Two classes of vehicles are considered: automobiles and trucks. These are the major types of vehicles on the highway. Other vehicle types do not exist in sufficient numbers so as to affect significantly the nationwide exposure expressed as L_{eq}. For simplicity, buses are included in the truck category.

If fleet energy-average automobile and truck noise levels are given by L_A^{eq} and L_T^{eq}, respectively, it follows from Equation (3) that:

$$L^{eq} = 10 \log_{10} \left[(1 - \eta)\ 10^{L_A^{eq}/10} + \eta 10^{L_T^{eq}/10} \right] \qquad (4)$$

where η is the fraction of trucks. The program thus calculates exposure as a function of L_A^{eq} and L_T^{eq}, permitting separate evaluation of automobile and truck noise abatement. The program can be extended easily to allow other vehicle classes, if this refinement is ever considered to be necessary.

Although the program permits unlimited variations in vehicle speed, numbers of traffic lights for each road element, and tract-by-tract variations of the propagation constant, limited availability of data requires the following three assumptions:

- $K = 1.5$ everywhere. This is a typical value observed in roadside measurements over clear terrain,[1,3] and is the value most often used in highway noise design guides.
- Only two road speeds are considered: 55 mph (88 kmh) and 35 mph (56 kmh). Actual speeds are known only in specialized cases. Freeways, rural roads, and major arterials in lightly populated areas are considered to be high speed, 55 mph (88 kmh). Urban streets and secondary suburban roads are considered to be low speed, 35 mph (56 kmh).
- Three traffic lights per mile (1.9 per kilometer) in all urban areas, based on data summarized in Appendix C.

2.2.2 Model Calculation

The noise model performs the following calculations:

- For each road element, distances to L_{eq} contours of 55, 60, 65, 70, 75, and 80 dB are computed.

- Distances between successive contours are multiplied by road element length to give area exposed to L_{eq} bands of 55-60, 60-65, 65-70, 70-75, and 75-80 dB. It is assumed that there is a 50-foot (15 meters) setback with no population, so that areas less than 50 feet (15 meters) from the road are not counted.
- Areas formed between pairs of adjacent L_{eq} contours are added over all road elements within each tract and multiplied by population density of that tract to give people exposed.
- The numbers of people exposed to each L_{eq} band for each tract are then summed over all tracts to give the total exposed in the city.

2.2.3 Representation of Exposure

The basic output of the program is the total number of people living within the five L_{eq} bands noted above. This is integrated to give the cumulative distribution of people exposed to levels greater than a particular L_{eq}, the format of exposure in Reference 5.

Representation of exposure in terms of day-night equivalent level L_{dn} requires calculation of day and night levels. Traffic flow data used in this study generally gave only 24-hour averages. Some day-night splits were available from specific traffic-counting stations. These data fall in the range 86 percent day/14 percent night to 89 percent day/11 percent night. Assuming an 87/13 split (the most typical value) for both automobiles and trucks, L_{dn} is simply related to the energy-average over 24 hours, $L_{eq}(24)$, by

$$L_{dn} = L_{eq}(24) + 3.3 \text{ dB} \qquad (5)$$

Exposure in terms of L_{dn} may be obtained by shifting appropriately the axes of the L_{eq} distributions.

As a basis for general comparisons, it is useful to represent exposure by a single number, rather than the complete distribution. Within this study, basic discussions of exposure are in terms of the number of people exposed to $L_{dn} \geq 65$ dB. This is a reasonable selection of a level above which adverse noise reaction would be expected. For example, it corresponds approximately to NEF $\geq$ 30 used for aircraft noise analysis.

The use of $L_{dn} \geq 65$ dB should not be taken here as a selection of a criterion, however, but as an example. Parallel calculations for the number of people exposed to $L_{dn} \geq 60$, 70 and 75 dB are presented in Appendix D.

2.3 Population Model

2.3.1 Population in 1970

Table 1, based on data in Reference 6, shows the distribution of the 1970 U.S. urban population living in places of 2,500 people or more. This table covers 133,500,000 people of a total 1970 urban population of 149,400,000. The distribution is arranged according to total size and average population for each place. Each city has sections where population density varies considerably from the mean.

The approach taken in the present study is to select sample cities of various size and density, compute exposure based on local traffic and population data, and use Table 1 to project this to the total urban population. Rural exposure is estimated separately, as discussed in Section 2.6.2, and is negligible in comparison to urban exposure.

Table 1 represents a joint distribution of city size and average city-wide population density. It was desired that sample cities be selected which give a good representation of the distribution ofcity size and local population density. Local density was considered to be important because of the microscale nature of the exposure calculation. City size is important because it can have an overall effect on local conditions, e.g., one city with a population of 200,000 would not necessarily have the same local conditions as ten cities each with a population of 20,000 and similar average density. Within a given city there is a distribution of local population densities. It was therefore decided to select cities of various size whose average densities were average among cities of that size. The variation of total size, and the tract-to-tract variations of density, would thus provide the desired distribution.

A list of candidate cities was selected partly on this basis, and partly by using criteria similar to those used in Reference 7 to select a "typical" medium city.* Table 2

* The criteria defined in Reference 7 were that a city have the highest number of median values of parameters assumed to influence indirectly community noise (i.e., population density, vehicle ownership, transportation industry activity, etc.).

Table 1

Approximate Percent Distribution 1970 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		2.0	(2) 1.1	(1) 3.9	5.7	13.6
500,000 - 1 Million		0.5	1.5	2.6 (4)	1.0	(3) 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	(7) 2.2 (8)	3.4 (6)	(5) 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 (9)	(10) 2.3	2.7	1.8	0.5	0.1	0.1	13.4
10,000 - 25,000	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 - 5,000	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%

(1) Chicago, Ill.
(2) Detroit, Mich.
(3) Milwaukee, Wis.
(4) Columbus, Ohio
(5) Rochester, N.Y.
(6) Lexington, Ky.
(7) Spokane, Wash.
(8) Jackson, Miss.
(9) Paducah, Ky.
(10) Bismarck, N.D.

* As defined in "Population of Places of 2,500 or More: 1970 and 1960", PC(S1)-26, U.S. Bureau of Census.

** Total of $133,5 \times 10^6$ living in 6,435 places considered in PC(S1)-26.

*** Numbers corresponding to sample cities are graphically located, with rows and column headings treated as approximate coordinate axes.

lists the final selection of ten cities which were used in this study. They were grouped into four size categories noted in Table 2. The size and density ranges for the cities are also noted in Table 1. The numbers in parentheses are located graphically on Table 1 with row and column headings treated as approximate coordinate axes. Local traffic authorities were contacted in candidate cities to obtain traffic flow maps and volume data. Population data were obtained from 1970 Census Bureau tract reports.[8]

Table 2
Sample Cities and 1970 Population Statistics

Size Category	Population Range	City	Population (Thousands)	Population Density (People Per Sq.Mi.)
Very Large	$>10^6$	Chicago, Ill. Detroit, Mich.	3,367 1,511	15,100 11,000
Large	$250K - 10^6$	Milwaukee, Wis. Columbus, Ohio Rochester, N.Y.	717 540 296	7,500 4,000 8,100
Medium	50K - 250K	Lexington, Ky. Spokane, Wash. Jackson, Miss.	108 170 154	4,700 3,400 3,100
Small	< 50K	Paducah, Ky. Bismarck, N.D.	32 35	2,700 3,200

Table 3 shows the distribution of the U.S. population (1970 census) according to the four city sizes defined here plus rural population. The noise exposure for the entire nation is obtained by multiplying the fraction of people exposed in cities of each size category by the population totals in Table 3.

Table 3

Total 1970 Urban* and Rural Populations

Category	Population	Total %
Very Large City $>10^6$	20.2×10^6	10.0
Large City 250K - 10^6	26.6×10^6	13.1
Medium City 50K - 250K	35.6×10^6	17.6
Small City <50K	66.3×10^6	32.7
Rural	53.8×10^6	26.6
TOTAL	203×10^6	100.0

* Includes the 133.5×10^6 tabulated in Table 1 plus population living in urban areas not considered to be places or which have a population of less than 2,500.

2.3.2 Population in Future Years

In years beyond 1970, the population of the U.S. will change in two ways: first, there will be an overall growth; second, there will be a shift in city size and density, so that the distribution will change from that shown in Table 1.

The approach taken in this study for future years was to retain the city size categories as defined in the first column of Table 3, and to develop growth factors for each size category. The demographic data for each of the sample cities are unchanged, with the viewpoint that they were chosen as examples of a particular size and density, and not for their own sake. For example, if population were to double, there would be twice as many cities in the medium-size range, so that the exposure calculated for Lexington, Spokane, and Jackson in 1970 would be projected to twice as many people. The 1970 demographic properties of these three cities are assumed to correspond to the future properties of whatever cities are then typical in this size category.

This approach carries with it the assumption that the correlation between density and city size does not change significantly in future years.

To develop future populations for the city size categories, population projections through 1990 made by the U.S. Department of Commerce[9] were used. These projections were based on demographic and economic analysis of Census Bureau data. The overall growth is keyed to the Census Bureau's series "E" national population projection, which assumes a fertility rate in 1990 roughly the same as the current rate. The projections in Reference 9 give future populations for the nation as a whole and in each of 253 Standard Metropolitan Statistical Areas (SMSA). The SMSA's are individually defined to include complete metropolitan areas, not just the area within a city's boundary. For an essentially self-contained city such as New York City, the SMSA includes a relatively small area outside the city boundary. For a city with extensive adjacent suburban areas, such as Washington, D.C., the SMSA includes a regional population several times greater than the city itself. It is typical for an SMSA to have twice the population of the city it contains.

Figure 5 shows the distribution of present and future SMSA sizes. The figure shows the fraction of total U.S. population living in SMSA's of a given size or greater in 1971,

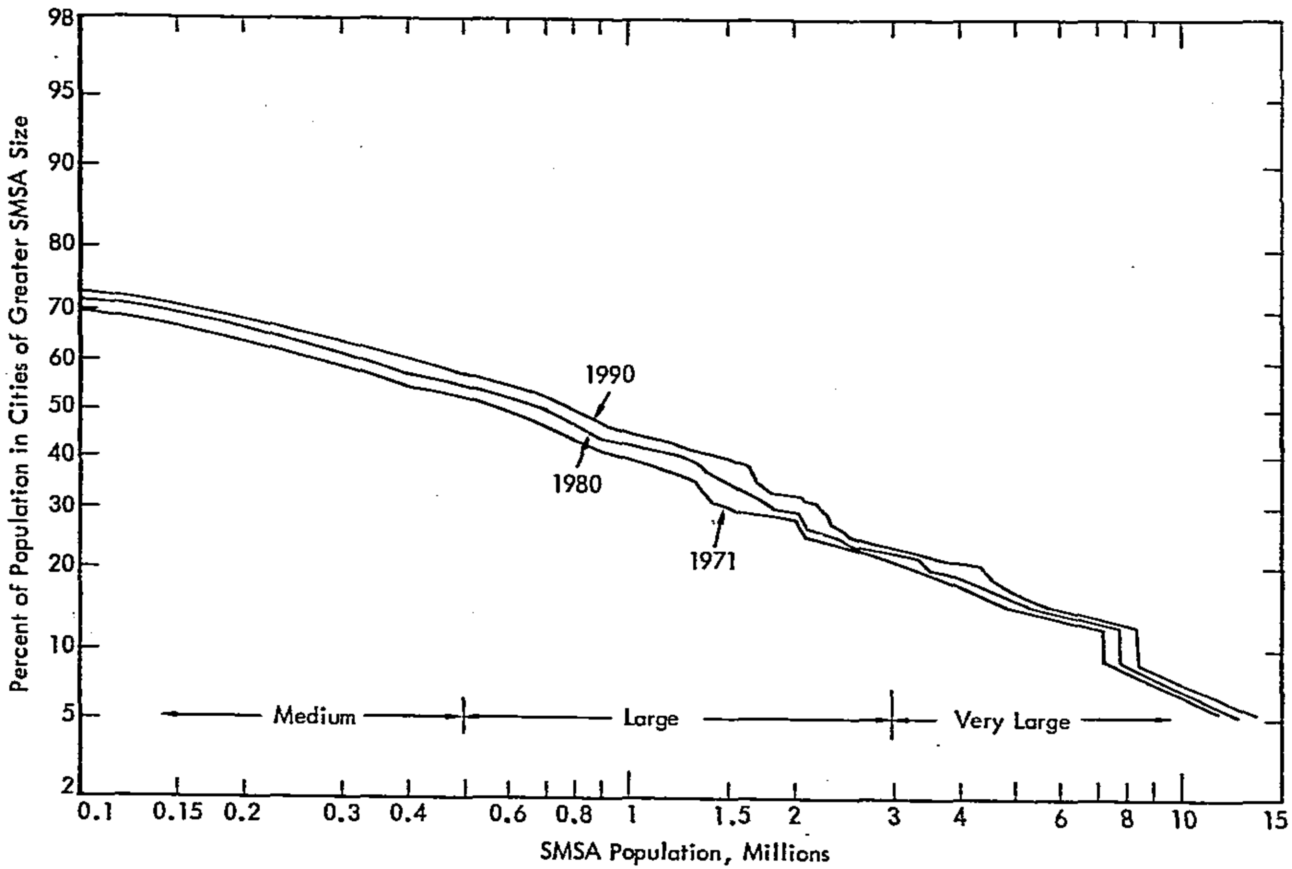

Figure 5. Distribution of U.S. Population by SMSA Size in 1971, 1980, and 1990.

1980, and 1990. These distributions were developed directly from the data of Reference 9, and correspond to the years given therein.* The distributions are quite similar, and fall close to a log normal distribution. The departure at small sizes is because the SMSA's do not represent a complete sampling of smaller cities. The consistent behavior of the SMSA size distribution supports the assumption that the city size/density relationship of Table 1 will not significantly change in character as total national population increases.

Growth factors for the four city size categories were obtained from growth of similar categories of the SMSA's. Table 4 lists the city size categories and the corresponding SMSA size ranges. The SMSA size ranges were determined by grouping SMSA's according to the 1970 population of the central city of each, so that these groupings represent approximately the same cities as the original city size categories.

Note that the distributions in Figure 5 show more people in each size category than Table 3 shows. This is because the SMSA's contain surrounding suburban areas as well as the core cities. In the present study, the SMSA data are used only to obtain growth rates, and it is assumed that the growth rate of a city is the same as for the SMSA.

Future growth factors were determined from the total population of SMSA's with future populations within the four size ranges. Growth factors were determined for the intervals 1971-1980 and 1980-1990, corresponding to the years reported in Reference 9.

Table 4

Central City and SMSA Population Ranges for City Size Categories

Size Category	City Population	SMSA Population
Very Large	$>10^6$	$>3 \times 10^6$
Large	$250K - 10^6$	$500K - 3 \times 10^6$
Medium	50K - 250K	100K - 500K
Small	< 50K	< 100K

* Reference 9 contains population data for 1950, 1969, 1971, 1980, and 1990.

Intermediate years were calculated using an exponential interpolation; years from 1990-2000 were calculated using an exponential extrapolation at the same growth rate as the 1980-1990 interval. Because the SMSA's did not contain an adequate sampling of small cities, growth of these was assumed to be the same as for medium cities. This may have resulted in an underprediction of small city population. Noise exposure in small cities is relatively small (see Section 2.6), however, so that the total national exposure would not be greatly affected.

Table 5 lists the population in each category, plus total U.S. population for 1970, 1980, 1990, and 2000.

Table 5

Estimated Distribution of U.S. Population by City Size Category

	Population (Millions)			
Size Category	1970	1980	1990	2000
Very Large	20.2	23.0	26.2	29.9
Large	26.6	29.7	34.1	39.1
Medium	35.6	36.8	38.0	39.2
Small	66.3	68.6	70.8	73.1
Rural	53.8	64.9	76.9	90.1
Total U.S.	203	223	246	271

2.4 Future Motor Vehicle Utilization

Estimates of future motor vehicle utilization, in terms of vehicle mileage, were obtained from two recent interagency reports.[10,11] These reports represent the most recent projections for future motor vehicles, and form the basis for fuel consumption estimates. Some aspects of future-use projection in these two reports may not be entirely satisfactory when applied to the present study. This is far outweighed, however, by the benefit of being consistent with other studies which utilize this data base.

2.4.1 Automobiles

Future projections in "The Report by the Federal Task Force on Motor Vehicle Goals Beyond 1980"[10] assume a 2-percent-per-year growth rate for new car sales. Total fleet size and vehicle miles travelled increase at slightly faster rates. This is for the baseline case of automobiles essentially unchanged in design from the present. Several alternative scenarios of fuel-efficient and improved safety automobiles are considered. An economic analysis was used to estimate automobile use for these scenarios, relative to the baseline scenario. The alternate scenarios, which all include better fuel economy, result in greater vehicle use than baseline. The most extreme scenario results in approximately 15 percent greater automobile vehicle miles in the year 2000 than for the baseline case. In the present study, a 2-percent-per-year increase in automobile vehicle mileage is used for the baseline case.

2.4.2 Trucks and Buses

Future projections in "Interagency Study of Post-1980 Goals for Commercial Motor Vehicles"[11] are based on a combination of historic trends, projections of freight movement needs, and economic analysis. The truck fleet is divided into six weight categories, summarized in Table 6. Truck and bus fleet size and annual vehicle mileage for 1973 are shown.

Table 6

Truck Size Categories, and 1973 Truck and Bus Fleet Size & Mileage

Size Category	GVW (Pounds)	Fleet Size	Annual Vehicle Miles (Millions)
III-V	10,001-19,500	1,595,000	15,200
VI	19,501-26,000	2,143,000	18,400
VII	26,001-33,000	424,000	9,900
VIII	over 33,000	1,134,000	60,900
Buses	-	467,000	5,700

Reference 11 placed emphasis on Category VI and VIII trucks, so that future projections for these are more reliable than for the other categories. This emphasis was taken because these two categories account for the majority of truck fuel consumption, which was a major consideration of Reference 11. This emphasis is consistent with the needs of the present study. Categories III-V include many non-commercial vehicles, and future use of these is not expected to increase significantly relative to the other categories. These are also the quietest of trucks, with noise levels much closer to those of automobiles than to those of heavy trucks.[4,12] It is usual to consider only categories VI, VII and VIII (GVW > 19,501 pounds) as trucks when predicting roadside noise levels.[1] Of these three categories, VI and VIII account for almost 90 percent of the vehicle mileage.

Reference 11 provides present and future mileage projections for local, short-haul and long-haul use of each category of truck. Trends in use (e.g., Category VIII for intercity hauling and VI for local deliveries) are discussed. It should, in principle, be possible to estimate future growth of each category separately for urban and rural areas. In practice, however, not enough detail is presented in Reference 11. Data for long and short haul are not subdivided according to rural or urban. Long-haul trucks also include some mileage through urban areas.

For use in the present study, a truck mileage growth rate of 2.4 percent per year has been assumed. This is consistent with the overall (all trucks plus buses) growth in Figure I-7 of Reference 11. The growth of Category VIII trucks alone is approximately 2.2 percent per year; of Categories VI, VII, and VIII trucks together it is 2.9 percent. The potential error involved comparing the range 2.2 percent to 2.9 percent with the value of 2.4 percent used here is equivalent to about a 1/2 dB or less difference in roadside noise levels.

2.5 Vehicle Noise Levels

2.5.1 Existing Vehicle Noise Levels

Based on roadside measurements of automobile noise, the existing L^{eq} for automobiles is given by

$$L_A^{eq} = 71.4 \text{ dB} + 32 \log_{10} (V/55) \tag{6}$$

where V is vehicle speed in mph. This is based on data reported in Reference 13, and is consistent with data from a variety of sources summarized in Reference 14.

Based on roadside measurements of truck noise,[4] L^{eq} for medium and heavy trucks, prior to the introduction of the Interstate Motor Carrier Regulations, is given by

$$L_T^{eq} = \begin{cases} 87.5\text{ dB} + 20\log_{10}(V/55), & V > 35\text{ mph} \\ 83.6\text{ dB} & , V \leq 35\text{ mph} \end{cases} \tag{7}$$

Equivalent levels near traffic lights are discussed in Appendix C.

2.5.2 Component Noise Levels

An important objective of the present study is to identify needed technology — in terms of component source noise levels — required to achieve specific goals. There are a number of component noise sources on motor vehicles. Most vehicle noise sources are part of the driveline (engine, fan, exhaust, etc.), however, and their interrelationship is reasonably well understood, e.g., for trucks from the DOT quiet truck program.[15] Similar information for automobiles will soon be available from current automobile noise technology studies sponsored by EPA. Tires are the one major noise component which cannot be grouped with driveline components. It is therefore necessary to consider only two source components for each vehicle type, i.e., tires and driveline.

Comprehensive data of the type used to develop Equations (6) and (7) are not available for tires and drivelines separately. However, it is well established that tire noise has a $40\log_{10} V$ dependence,[16] while the speed dependence of driveline noise is substantially less. If the relative contribution of tire and driveline noise is known at some speed, then Equations (6) and (7) could each be decomposed into a tire noise relation with this speed dependence, and a driveline noise relation comprising the rest of the total.

One such decomposition is

Automobiles:

$$\left.\begin{aligned} L_{A_t}^{eq} &= 69.3 + 40\log_{10}(V/55) \quad , \text{ tires} \\ L_{A_d}^{eq} &= 67.3 + 23.7\log_{10}(V/55) \quad , \text{ driveline} \end{aligned}\right\} \tag{8}$$

Trucks ($V \geq 35$ mph):

$$L^{eq}_{T_t} = 85.2 + 40 \log_{10} (V/55) \quad , \quad \text{tires}$$
$$L^{eq}_{T_d} = 83.6 + 6 \log_{10} (V/55) \quad , \quad \text{driveline} \qquad (9)$$

These relations are shown in Figure 6. It should be noted that Equations (8) and (9) are consistent with (6) and (7) only at 35 mph and 55 mph. Points between are approximated with straight lines on a semi-log plot of noise level and speed.

It should also be noted that Equations (8) and (9), and Figure 6, are somewhat arbitrary, since Equations (6) and (7) and the $40 \log_{10} V$ speed relation are not sufficient to derive source decomposition. The decomposition given here should be treated as an example. However, the decomposition must fall within the constraints that:

- Neither component may exceed the total within the speed range shown.
- Noise at high speeds is dominated by tires.
- Noise at low speeds is dominated by driveline.

Within these constraints, any source decomposition must lie within approximately ± 2 dB of that presented here.

2.5.3 Future Noise Levels

Because of the growing shortages of fossil fuels, it is expected that there will be changes in the configuration of motor vehicles. The major reason for the studies reported in References 10 and 11 was, in fact, to assess these changes from a viewpoint of improved fuel economy. It is possible that vehicle configuration changes due to improved fuel economy may result in changes to noise levels. Any assessment of future noise impact must include an evaluation of these changes.

Future Automobile Noise Levels

Automobile noise levels, in terms of L^{eq}_A, may change in two ways:

- Shift in fleet mix to different size cars, which have different noise characteristics.
- Change in noise due to different technology, e.g., Diesel engines instead of Otto.

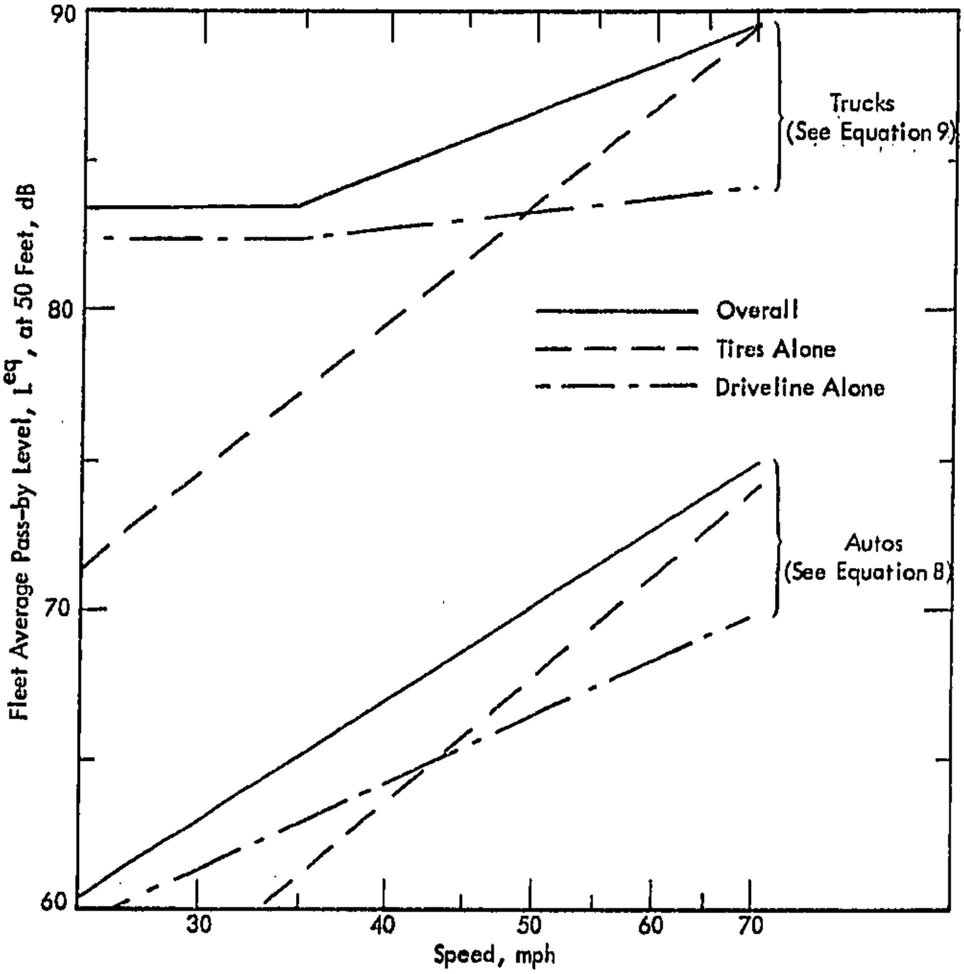

Figure 6. Automobile and Truck Noise Levels, and Decomposition Into Driveline and Tire Components

Recent measurements of noise from 1977 model automobiles[17] indicate that current small automobiles are 5 to 6 dB louder than large when operated under 0.15g acceleration, while there is no consistent correlation with size under cruise conditions. Limited data for Diesel-engined automobiles[17] indicate that they are approximately 5 dB louder than Otto-engined automobiles under cruise and acceleration conditions. An increase of 5 to 10 dB in automobile noise is thus possible if the automobile fleet were to become predominantly small with a large fraction of Diesels.

This kind of shift is not expected, however. Reference 10 considers projections through 1995 for several alternative fleet mix scenarios, defining automobiles as large (6 passenger), medium (5 passenger), and small (4 passenger). The present automobile fleet consists of 50 percent large, 25 percent medium, and 25 percent small. In the baseline case, with automobiles as today, the new automobile fleet will consist of 60 percent large, 25 percent medium, and 15 percent small (Figure 7-8 of Reference 10). Projections for other scenarios result in new automobile fleets of 50 to 60 percent large, 25 to 35 percent medium, and 15 to 25 percent small. Any shift in mix within these limits would result in L_A^{eq} changing by less than 1 dB. If a great shift to small automobiles occurred, L_A^{eq} would increase by 5 to 6 dB under acceleration. Acceleration accounts for less than one-third of the operating condition on low-speed roads (see Appendix A), so that the increase to L_A^{eq} averaged over operating modes would probably be no more than 2 to 3 dB.

A change in engine type could result in higher levels. Since Diesels are about 5 dB louder than Otto-engined automobiles, L_A^{eq} would increase 5 dB if a complete switch to Diesels occurs. Again, this is not likely. Reference 10 does not provide a firm basis for estimating potential changeover to Diesels, but it is consistent with Reference 10 to assume 25 percent of the fleet could be Diesel powered by 2000. This estimate would result in L_A^{eq} increasing by about 2 dB.

From the above discussion it appears that there will be an increase of less than 1 dB due to fuel economy considerations, unless there is a substantial shift to small automobiles and/or Diesels. In either of these cases, L_A^{eq} may increase by about 2 dB. The baseline impact calculations in the present study therefore assume no changes in L_A^{eq}, with the effect of a 2 dB increase in the year 2000 calculated as an alternate scenario.

Future Truck Noise Levels

The shift in truck fleet mix, in terms of data on vehicle mileage discussed in Section 2.4.2, is not substantial enough to affect L_T^{eq} significantly. There will, however, be a shift to more Diesel engines. Table 7 shows the percentage of vehicle miles associated with Diesel-powered trucks in 1973 and 1990 for each size category, and for all trucks. The change to Diesels would result in less than a 1 dB increase in L_T^{eq} even if Otto engine truck noise were negligible compared to Diesel noise. Even this slight increase in noise is not expected to occur, however, because Diesel trucks are and will be subject to noise regulations. These regulations will be felt most on new trucks, so that new Diesels will not be significantly louder than Otto trucks. The change in future L_T^{eq} will then be almost entirely due to current and proposed truck noise regulations.

Table 7

Percentage of Truck Mileage Due to Diesels*

	Truck Size Category**				
	III-V	VI	VII	VIII	All
1973	0	7	49	84	55
1990	0	65	91	98	82

* Based on data in Figure I-7 of Reference 11.

** See Table 6 for definitions.

2.6 Baseline (1970) Noise Exposure

Noise exposure has been computed using 1970 (the year of the last complete census) as the baseline. The general character of the exposure, including exposure as a function of city size and rural exposure, is discussed here for the baseline year.

2.6.1 Urban Noise Exposure

Table 8 shows the calculated results for the four city sizes in terms of the fraction of population exposed to various ranges of L_{dn}. Note that the percentage of population exposed to a given level increases with city size. One-third of the total urban population exposed to $L_{dn} \geq 65$ dB is in very large cities which account for only 13.6 percent of the urban population. Also note that the total fraction exposed to $L_{dn} \geq 55$ dB for very large cities is greater than one, while exposure to $L_{dn} \geq 60$ dB is almost one. This result occurs because the assumption of exposure to only one road at a time is invalid in large densely populated cities at low noise levels. In such cities, the residual noise level (which represents general background noise from many streets) is often 55 to 60 dB or more so that some people are counted more than once. It is consistent that the present calculation "saturates" at these levels, since the assumption that a given individual is exposed to noise from only one street is no longer valid. The predicted exposure to higher levels is not affected by this, however.

Table 8
Baseline Urban Population
Exposed to Highway Noise (1970)

City Size	Fraction Exposure to L_{dn} Range*				
	55 - 60	60 - 65	65 - 70	70 - 75	75 - 80
Very Large $>10^6$	(1.071)†	(0.497)†	0.229	0.084	0.019
Large 250K - 10^6	(0.640)†	0.297	0.134	0.044	0.009
Medium 50K - 250K	0.419	0.194	0.086	0.025	0.005
Small <50K	0.200	0.093	0.032	0.003	**
Average of all Urban	0.450	0.209	0.090	0.027	0.005

* Based on population totals given in Table 3.

** Less than 0.001.

† Calculated exposure not reliable due to non-linearities at high population density and low noise level.

2.6.2 Rural Exposure

Calculation of rural highway noise exposure in the same manner as urban exposure would require traffic and population data from a large number of locations. An estimate of rural exposure may be made, however, on the basis of available statistical data of rural travel. Reference 18 presents statistical distributions of traffic volumes on all federally funded highways in 1970. In rural areas, this constitutes the majority of traffic. Table 9 shows these data in the form of the number of miles of road with various traffic volumes. Truck percentages are taken as 9 percent, the national average.

Table 10 shows the calculated rural exposure. The areas exposed to various levels are computed directly from the traffic volume data in Table 9, assuming a 50-foot (15-meter) setback. The population exposed is obtained by assuming a density of 56 people/mi^2, the total U.S. population divided by the total area.

The rural exposure is small compared to urban exposure, and is probably less than the accuracy of the urban calculation. Rural exposure is therefore neglected.

2.6.3 Baseline Exposure

The national exposure to highway noise is given by the values in Table 8. A more useful representation of noise distribution is the cumulative distribution, i.e., numbers of people exposed to noise exceeding a given level. This is shown in Figure 7 for 1970. In addition to total exposure, Figure 7 shows exposure from high-speed (55 mph) and low-speed (35 mph) roads separately. Exposure to noise environments $L_{dn} < 70$ dB is primarily due to low-speed roads, while most exposure to $L_{dn} > 70$ dB is due to high-speed roads.

The importance of stop-and-go traffic is also seen in Figure 7. Shown are exposure distributions for no traffic lights. Low-speed exposure $L_{dn} \geq 65$ dB is about 20 percent lower if lights are neglected, with the difference greater at higher noise levels.

The relative importance of automobiles and trucks is shown in Figure 8. The exposure distributions have been computed for automobiles and trucks separately. Note that trucks are the dominant noise source for exposure to both high and low noise levels.

Table 9

Traffic Flow on Federally Funded Rural Highways, 1970

Average Daily Traffic (ADT)	Miles		
	Interstate	Primary	Total
<400	230	9,086	9,316
400 - 1K	769	36,453	37,122
1K - 2K	2,790	56,782	59,572
2K - 3K	3,567	38,418	41,985
3K - 4K	3,691	24,188	27,879
4K - 5K	3,577	15,426	19,003
5K - 10K	10,804	27,802	38,606
10K - 15K	5,131	9,164	14,295
15K - 20K	2,340	3,453	5,793
20K - 30K	1,362	1,868	3,230
30K - 40K	234	353	587
>40K	209	265	474

Table 10

Calculated Rural Population
Exposed to Highway Noise (1970)

	L_{dn} Range					
	55 - 60	60 - 65	65 - 70	70 - 75	75 - 80	Total
Area (mi^2)	23,400	10,700	4,300	1,200	150	39,750
People (millions) (56 people/mi^2)	1.310	0.599	0.241	0.067	0.008	2.225
Fraction of Rural Population	0.0244	0.0112	0.00449	0.00125	1.6×10^{-4}	0.0415

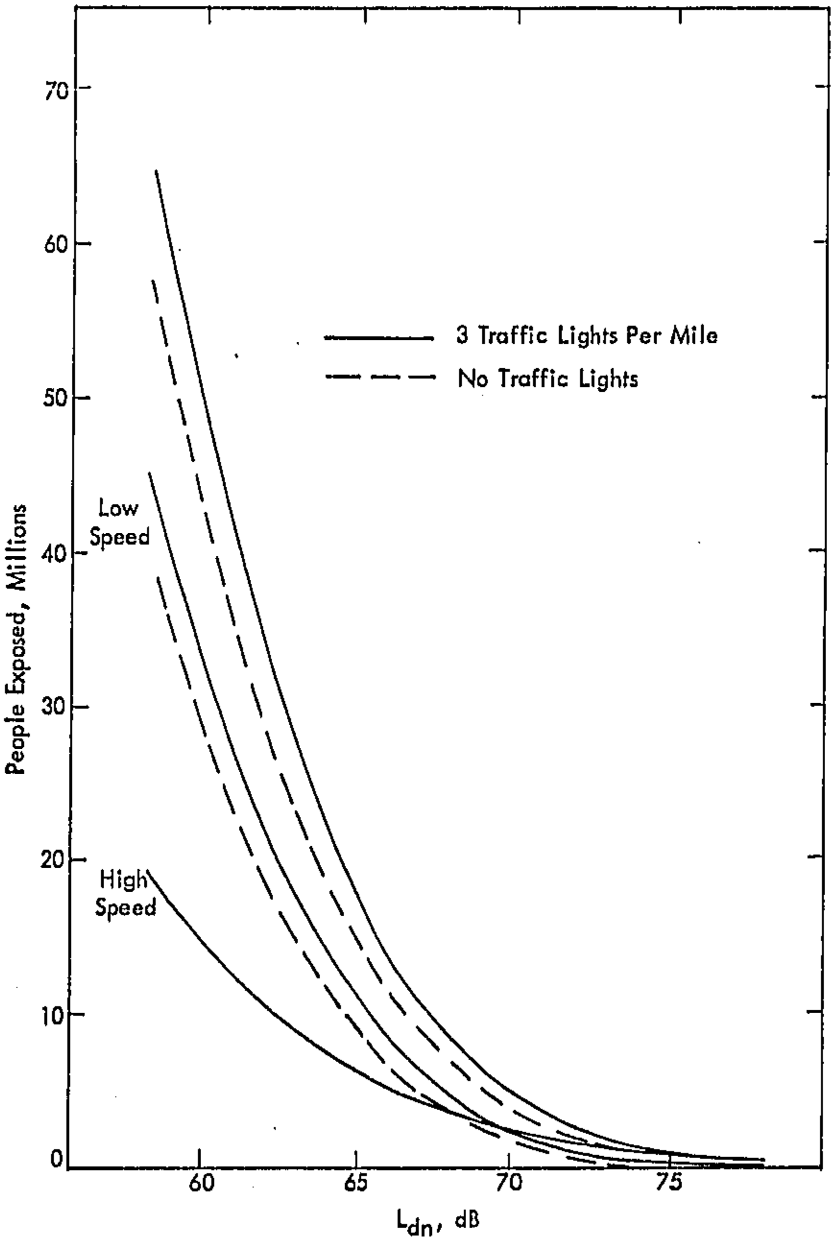

Figure 7. People Exposed to Levels Exceeding Various Values of L_{dn} in 1970.

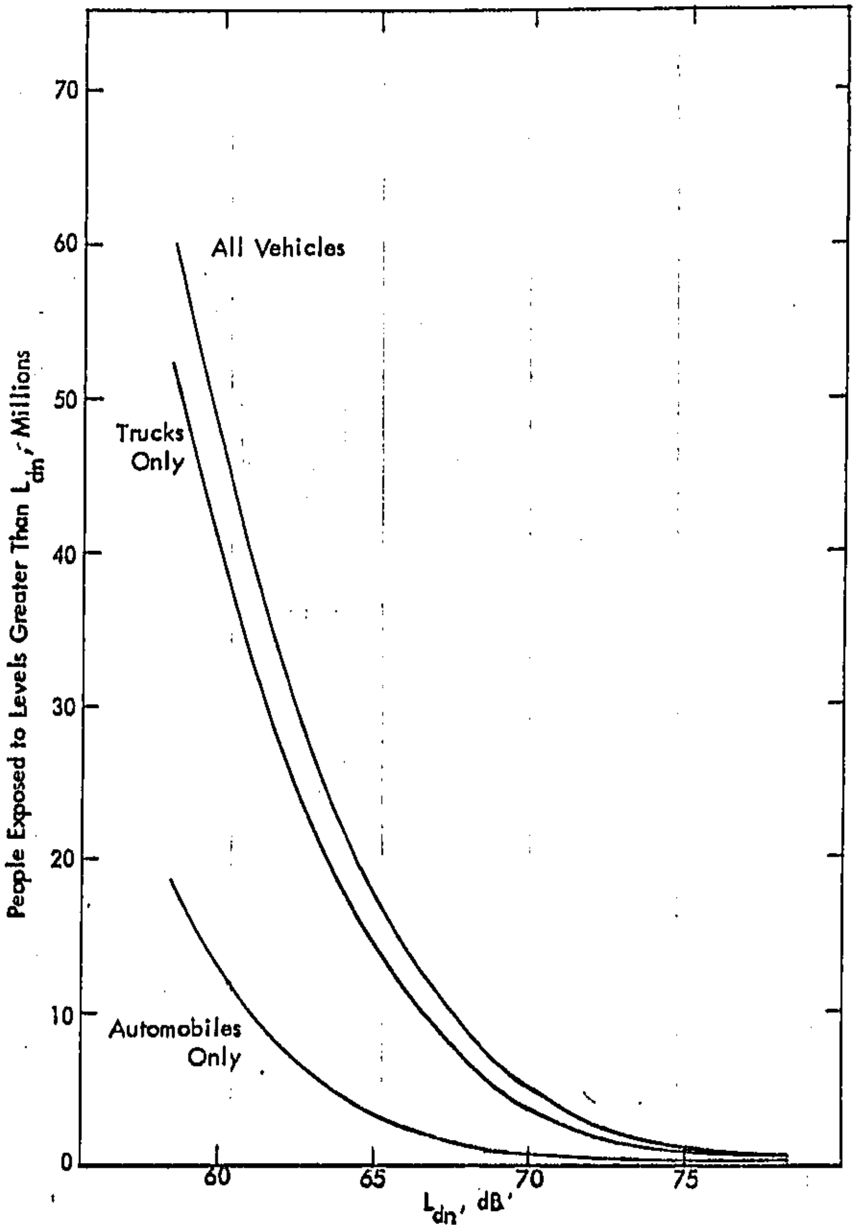

Figure 8. Noise Exposure Due to Automobiles Alone and Trucks Alone, 1970

2.7 Exposure to the Year 2000

Exposure has been calculated for the period from 1970 to 2000 for several alternative scenarios:

- No vehicle regulations. This shows the growth of exposure due to population and vehicle-use increases, if vehicle noise levels had remained unchanged.
- Existing truck regulations. These are the regulations promulgated by EPA: the Interstate Motor Carrier Regulation of 86 and 90 dB operating limits at low and high speeds, respectively, effective in 1975, and the low-speed new truck standards of 83 dB in 1978 and 80 dB in 1982.
- Existing truck regulations, plus a 75 dB new truck standard in 1985.
- A 45 mph (72 kmh) urban truck speed limit, in addition to the two truck noise regulation scenarios.
- A hypothetical improved Interstate Motor Carrier Regulation of 83 and 86 dB at low and high speeds, respectively, effective in 1985.

The effect of L_A^{eq} increasing by 2 dB in 2000 is shown for the first three scenarios noted above.

These calculations used vehicle and population projections through 2000. The reduced vehicle levels used for the truck regulatory scenarios were computed using HINCSAM, which was discussed in Section 1.2. Specific features of the HINCSAM calculation are discussed in Section 3.3, which contains a comprehensive discussion of the effect of regulations on L^{eq}.

Figure 9 shows calculated exposure, expressed as number of people exposed to $L_{dn} \geq 65$ dB, to 2000. Figure 10 shows exposure from high- and low-speed roads. Table 11 summarizes the exposure for 1970, 1977, and 2000.

There are a number of specific features to be noted in these results:

1. With no change to vehicle levels, the number of people exposed would have nearly doubled from 1970 to 2000. The fraction of the population exposed would have increased by about 50 percent.

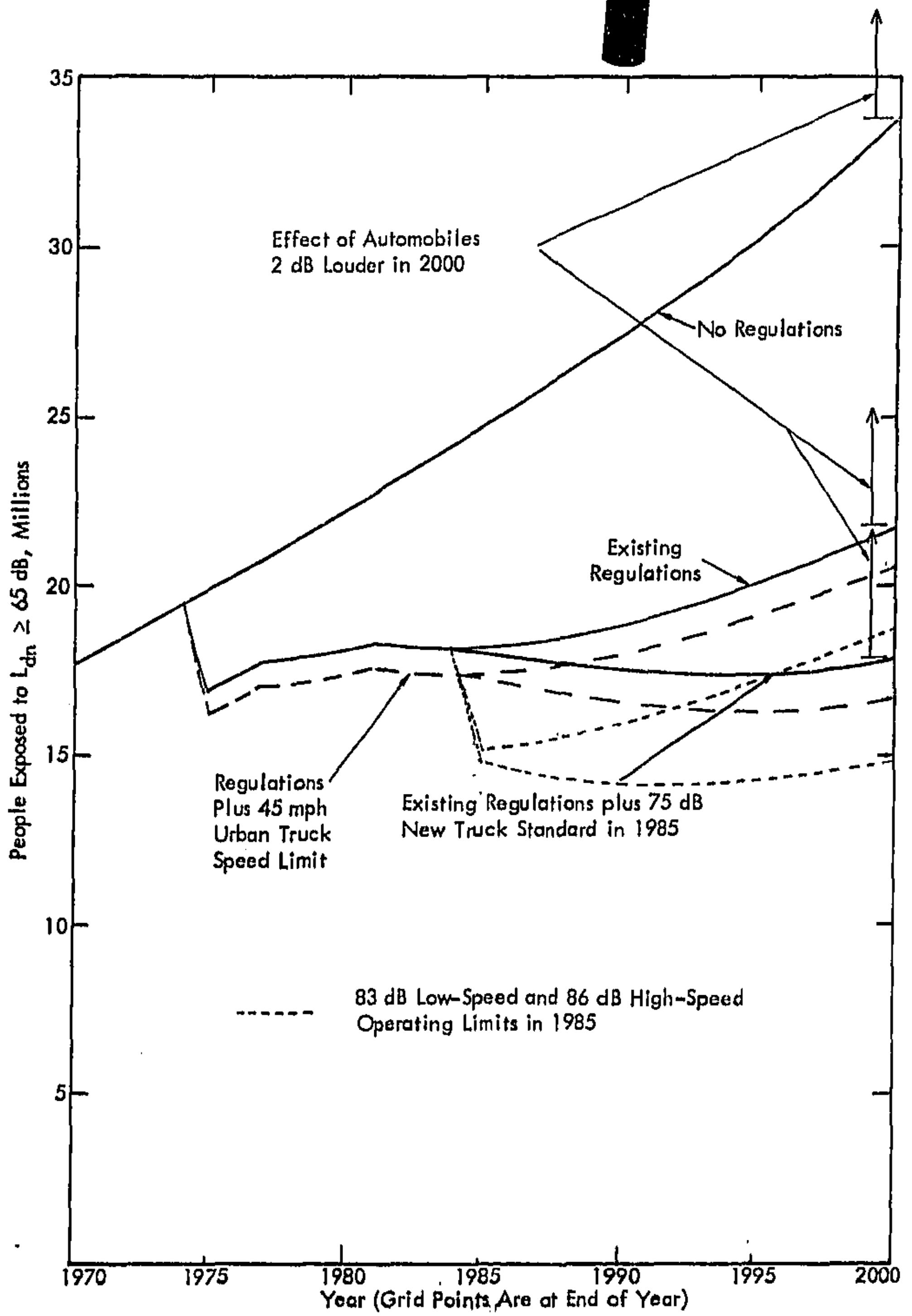

Figure 9. Effect of Truck Noise Regulations on Exposure to $L_{dn} \geq 65$ dB

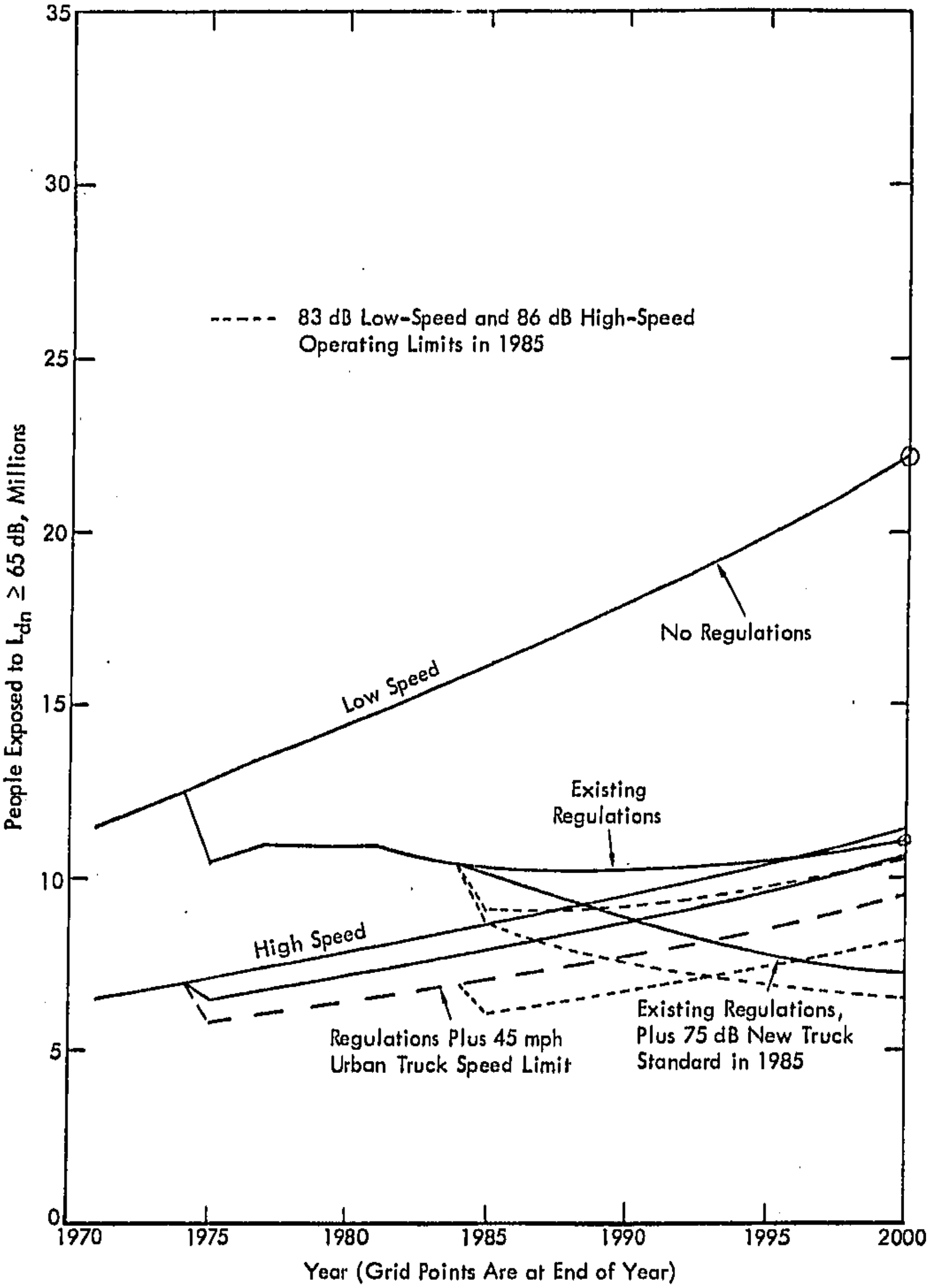

Figure 10. Exposure to $L_{dn} \geq 65$ dB From Low- and High-Speed Roads for Truck Noise Regulations.

Table 11

Summary of Exposure to $L_{dn} \geq 65$ dB for Several Scenarios

	1970		1977		2000	
Regulation Scenario	Millions of People	Percent of Population	Millions of People	Percent of Population	Millions of People	Percent of Population
No Regulations	17.6	8.7	20.8	9.6	34.6	12.8
Autos +2 dB in 2000	--	---	--	---	37.7	13.9
Existing Regulations	--	---	17.8	8.2	21.6	8.0
Autos +2 dB in 2000	--	---	--	---	25.2	9.3
Existing plus 75 dB New Truck Standard in 1985	--	---	17.8	8.2	17.8	6.6
Autos +2 dB in 2000	--	---	--	---	21.5	7.9
Existing plus 45 mph Urban Truck Speed Limit	--	---	17.0	7.8	20.5	7.6
Existing plus 83/86 Operating Limits in 1985	--	---	17.8	8.2	18.8	7.0
Existing plus 83/86 Operating Limits plus 75 dB New in 1985	--	---	17.8	8.2	14.2	5.3

2. With existing truck regulations, the number of people exposed will increase by 23 percent, while the fraction of total population exposed will decrease slightly.

3. Adoption of a 75 dB new truck standard in 1985 would result in future numbers exposed being about the same as 1970, with a decrease in the fraction exposed.

4. The benefit from existing and proposed truck regulations is primarily at low speeds. The existing motor carrier regulation reduces high speed exposure by about 10 percent. A 45 mph urban truck speed limit would have a similar additional benefit.

5. Adoption of reduced in-use operating limits would give an immediate benefit over the short term. After a number of years, a new vehicle standard (which can specify a lower level) would provide still further reduction to exposure.

6. To fully realize the benefits of reduced truck noise levels, automobile noise levels should not be permitted to increase. A 2 dB increase in L_A^{eq} in 2000 would negate the benefit of a 75 dB new truck standard.

In addition to these specific features, the overall nature of this projection is significant. Inclusion of growth in the present calculation shows the change in exposure to be a dynamic process. Abatement schemes must be dynamic as well. While the scenarios computed above show various degrees of short- and long-term abatement, after some point they all display increasing exposure. To maintain some given exposure level, vehicle noise limits must periodically be reduced. Because achievable vehicle noise levels are always limited by available technology, there is a need for a continuing program of research and development in vehicle noise reduction technology.

3.0 REDUCTION OF HIGHWAY NOISE EXPOSURE

3.1 Exposure for Reduced Vehicle Levels

The number of people exposed to $L_{dn} \geq 65$ dB in 2000 has been computed as a function of vehicle noise level reduction. This is shown for low- and high-speed roads in Figures 11 and 12, respectively. The quantities ΔL^{eq} are the difference between assumed L^{eq} and baseline (1970) L^{eq}. Indicated on the figures are the number of people exposed in 1970, and the three baseline cases of no regulations, existing regulations, existing plus improved motor carrier, and existing plus 75 dB new truck standard.

Figures 11 and 12 show the relative significance of automobiles and trucks, respectively, and the interrelationship of reducing the noise from each. From the no-regulation case, reducing L_A^{eq} alone would give very little benefit. After L_T^{eq} is reduced, however, the ΔL_A^{eq} curves become more widely spread, so that a significant benefit can then be achieved by quieting automobiles. The $\Delta L_A^{eq} = 0$ curve levels off at large reductions to L_T^{eq}, so that exposure reduction is limited at some point if only trucks are quieted.

For an objective of reducing exposure to a given number of people, the required combination of vehicle noise reduction may be identified from Figures 11 and 12. For example, a low speed exposure of less than 10^6 people could be achieved with the combination $\Delta L_A^{eq} = -15$ dB and $\Delta L_T^{eq} = -8$ dB, or with $\Delta L_A^{eq} = -10$ dB and $\Delta L_T^{eq} = -9$ dB, etc.

The concept of alternate combinations of reductions between the two sources, and limits of benefit of reducing only one, may be seen more clearly in Figures 13 and 14. These are cross-plots from Figures 11 and 12, and show combinations of ΔL_A^{eq} and ΔL_T^{eq} required to reduce exposure in 2000 to a given percentage of 1970 exposure. Shown for reference on these and following figures are ΔL_A^{eq} and ΔL_T^{eq} calculated for the year 2000 for three scenarios. The relation between a specific regulatory limit and L^{eq} is discussed in Section 3.3. Note that the curves become parallel to the axes at large ΔL^{eq}; this represents the condition where noise is dominated by one vehicle type, so that further quieting of the other has no benefit. Note that quieting automobiles alone cannot make the exposure in 2000 equal to or less than half of the 1970 exposure. Also, among the curves shown, high speed exposure cannot be reduced to 50 percent of 1970 and low speed to 20 percent unless automobile noise, as well as truck noise, is reduced.

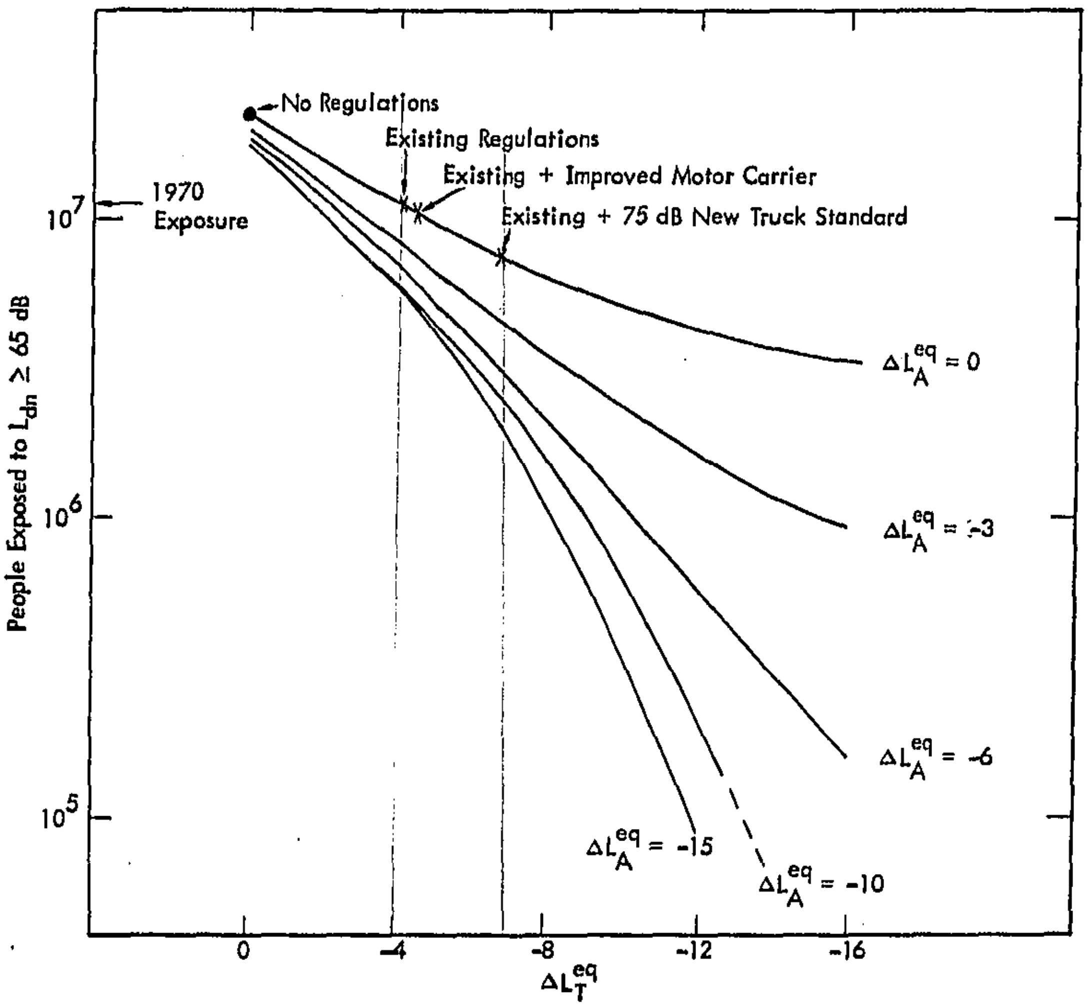

Figure 11. Exposure to $L_{dn} \geq 65$ dB From Low-Speed Roads in 2000 For Various Reductions to Automobile and Truck Noise

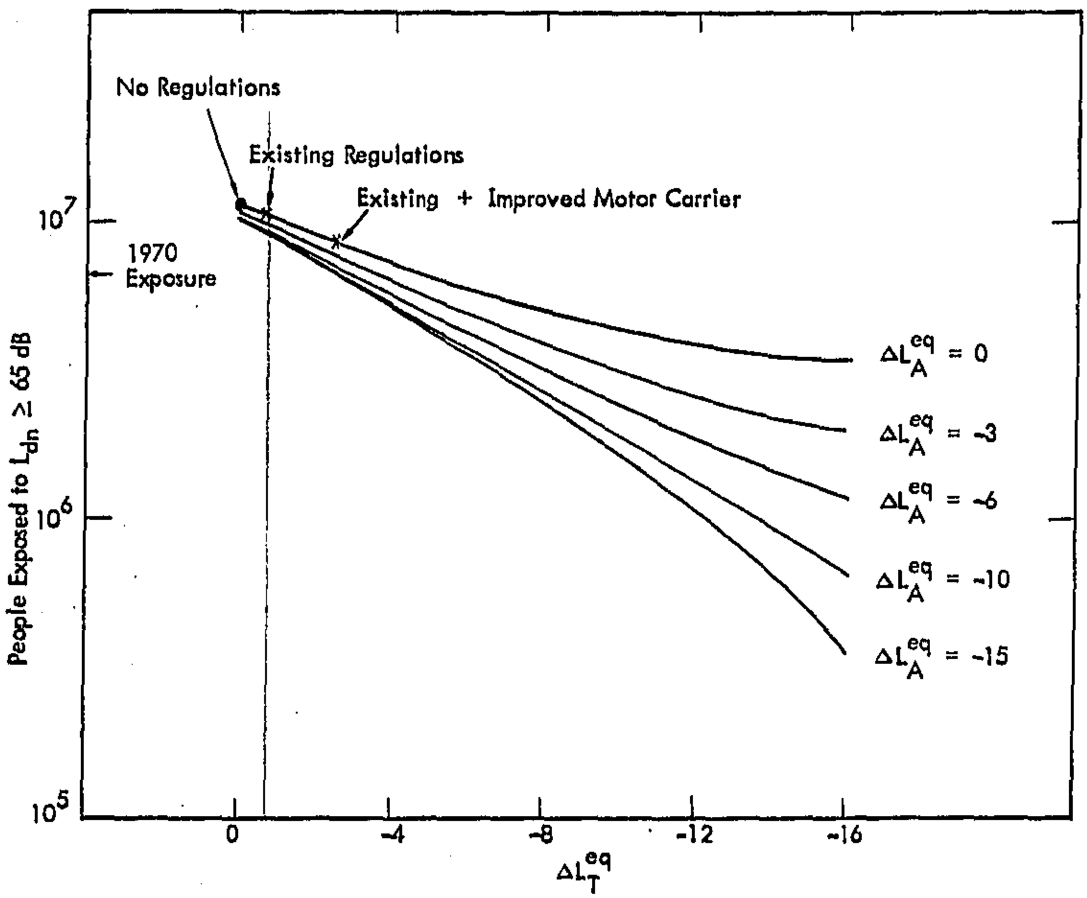

Figure 12. Exposure to $L_{dn} \geq 65$ dB From High-Speed Roads in 2000 For Various Reductions to Automobile and Truck Noise

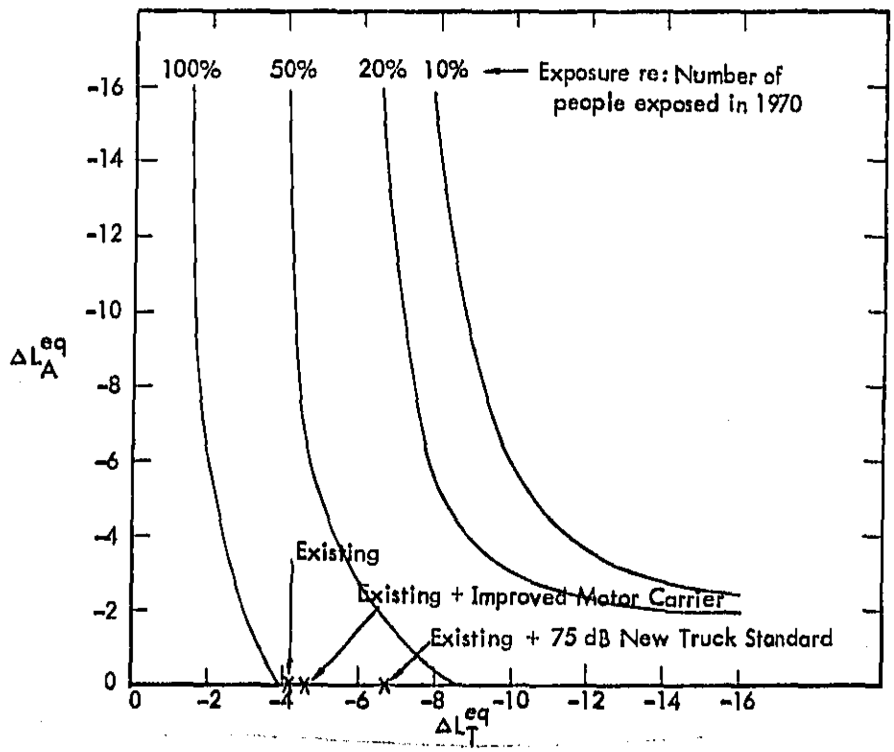

Figure 13. Vehicle Noise Reductions Required to Reduce Low-Speed Exposure in 2000.

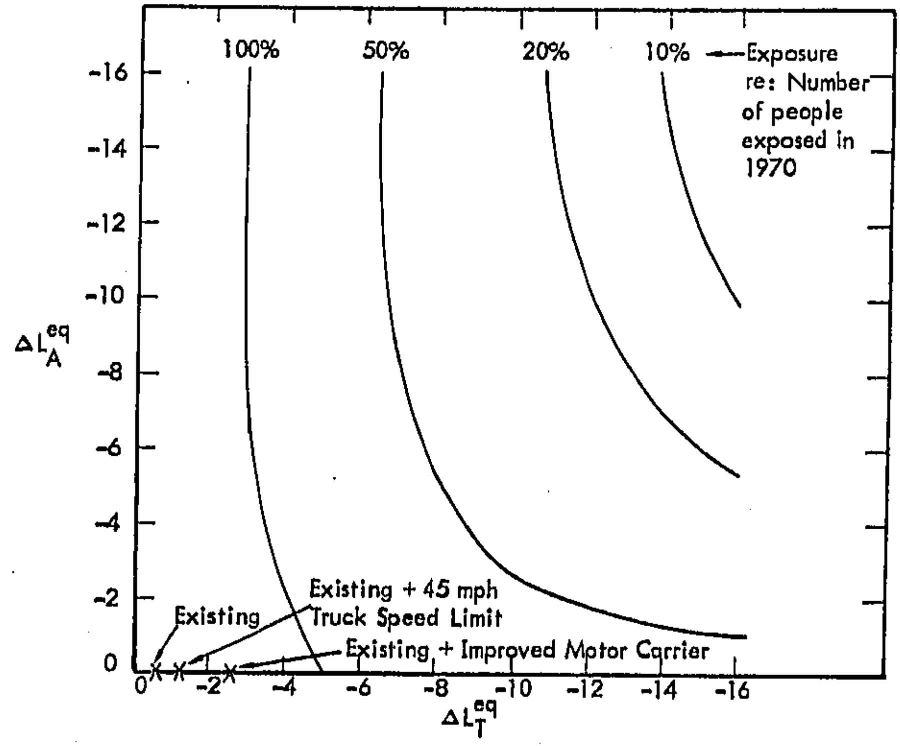

Figure 14. Vehicle Noise Reductions Required to Reduce High-Speed Exposure in 2000.

3.2 Component Noise and Required Technology

A limiting situation similar to that seen in Figures 13 and 14 exists for vehicle levels when the separate sources of tires and driveline are considered. If driveline noise were completely eliminated, vehicle levels would be given by the tire component of Equations (8) and (9); if tire noise were eliminated, driveline noise would remain. Table 12 summarizes the vehicle noise reduction, ΔL^{eq}, which could be achieved if noise from only one of these two sources is reduced, based on the example source decomposition of Equations (8) and (9). Shown for reference in Table 12 are the values of ΔL^{eq} expected in 2000 due to existing regulations, without regard to how these are achieved with regard to tires and/or driveline. It is straightforward to note these values of ΔL^{eq} on Figures 11 through 14 to see the limitations on impact reduction if only one source component is reduced. Figures 15 and 16 show these limits on the same plots as Figures 13 and 14.

Table 12

Vehicle Noise Reduction
Eliminating One Source Component Only

Component Eliminated	Vehicle Type	ΔL^{eq} (dB) Low Speed (35 mph)	High Speed (55 mph)
Driveline	Trucks	-6	-2
	Automobiles	-4	-2
Tires	Trucks	-1	-4
	Automobiles	-2	-4
Expected from Existing Regulations	Trucks	-4.2	-0.6
	Automobiles	---	---

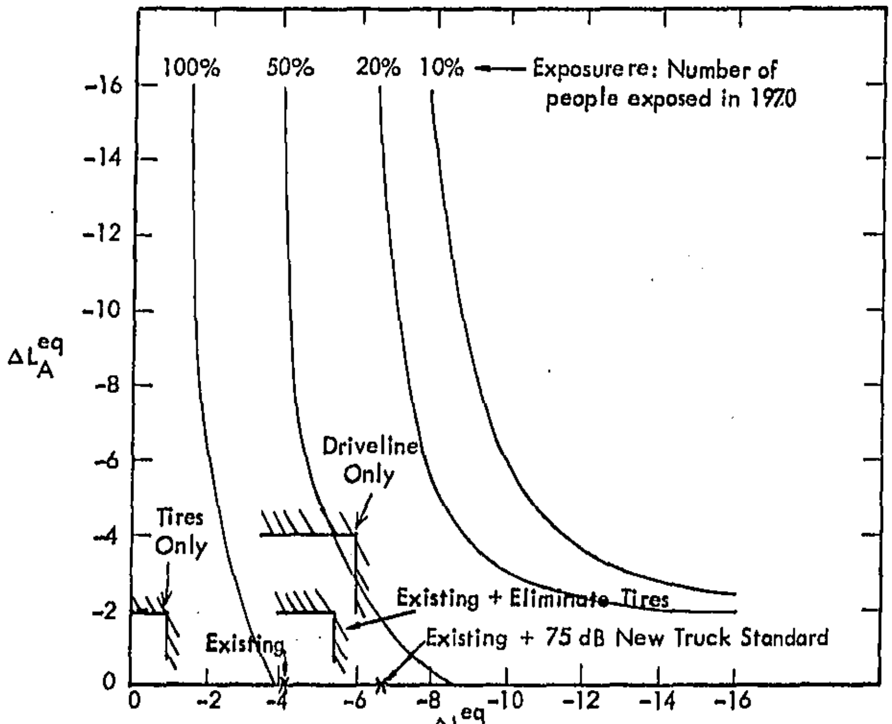

Figure 15. Limitation of Low-Speed Exposure Reduction in 2000 if One Source Component Is Reduced.

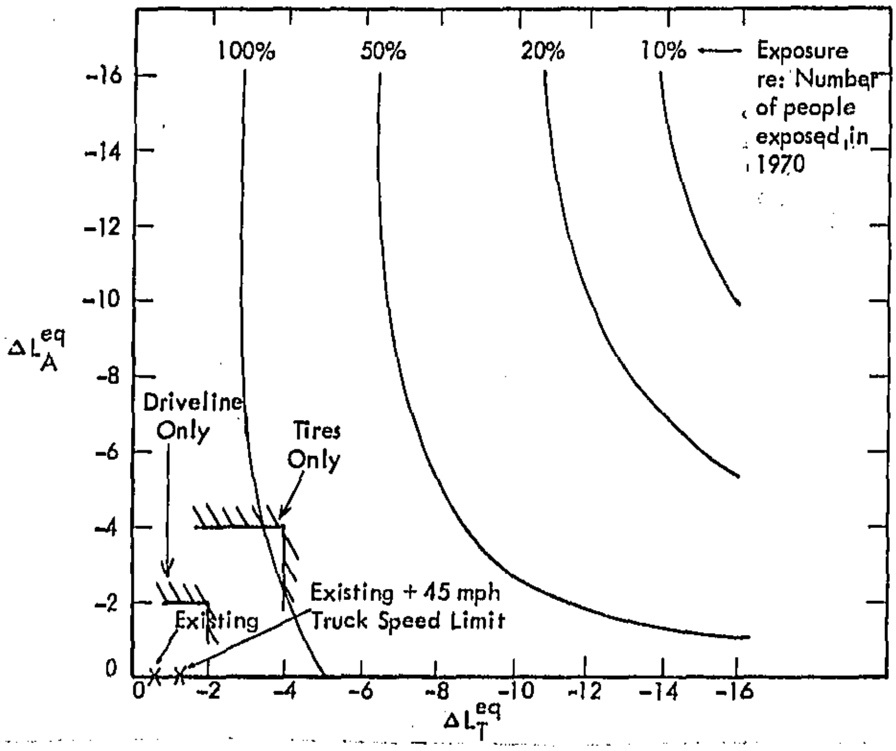

Figure 16. Limitation of High-Speed Exposure Reduction in 2000 If One Source Component Is Reduced.

It is seen on Figures 15 and 16 that if driveline noise alone were eliminated, low speed exposure in the year 2000 can be reduced to about half of the 1970 exposure, while high speed exposure will still increase as population and traffic grow with time. This kind of behavior is inherent in current and possible future truck regulations, which essentially are limited to driveline noise, and is seen in Figures 11 and 12. To achieve substantial reduction in exposure, i.e., reduce it to less than half of the 1970 exposure, tire noise reduction will be required.

Tire noise generation mechanisms are not yet well understood. Measurement studies, such as Reference 16, have determined the noise levels of various existing tire types, and have established certain scaling laws such as the $40 \log_{10} V$ relation, and the effect of load and air pressure. A qualitative understanding of desirable and undesirable tread designs have been achieved, and it is possible to identify the quietest existing design. Beyond this empirical work, however, little understanding of tire noise has been achieved. Several theories, based on conflicting assumptions, fit the available data equally well. Until such time as tire noise generation mechanisms are better understood, vehicle noise reduction will be limited by tire noise. There is a strong need for basic tire noise research, and this need will grow as reductions in driveline noise result in tire noise being more dominant.

3.3 Noise Reduction Options

The general concepts of vehicle noise reduction controls were discussed in Section 1.2. Beginning with an existing population of vehicles such as shown in Figure 2, noisy vehicles at the extreme of the distribution could be eliminated and/or quieted. This could be done either immediately (in principle) through an operating regulation, or over a period of time with a new vehicle standard. The final effect is described in terms of L^{eq}, computed from the vehicle histogram resulting from vehicle regulations. The mathematical development of this calculation is presented in Reference 1, together with a computer program which performs the calculation for a given scenario.

In this section, the assumptions used in the calculation are reviewed, and generalized results are presented for the two types of regulation.

3.3.1 Operating Regulations

The principle of an operating regulation is that vehicles will not be permitted to emit noise over a specified limit. Vehicles over the limit may be brought into compliance by retrofit or repair, or they may be replaced. A retrofitted vehicle would be expected to be brought just into compliance, because retrofit kits would be specifically designed for this purpose. A repaired vehicle could be less than the limit in those cases where the vehicle would normally be quiet.

Two other possibilities are noisy vehicles being left as they are, and vehicles already below the limit being reduced further. The first is a matter of operators not complying, and is an enforcement problem. The second would be the case of an operator making repairs to a normally quiet vehicle even though it is not in violation (e.g., replacing a deteriorating muffler before it actually exceeds the regulatory limit), or an operator with a positive attitude towards doing more than is required.

Except for vehicles which are retrofitted and those which are left alone, it is not possible to estimate realistically changes to the distribution. To handle those which are left alone, it is necessary to assume a compliance rate. Vehicles which are replaced or repaired may be brought below the regulated limit. If it is assumed that the only modification is retrofit, then a conservative result will be obtained which shows the minimum expected benefit. Actual benefit would probably not be much greater, because a realistic operating limit would usually be set at a level which could be met reasonably, but not at one which could be bettered easily by many vehicles.

For purposes of this study, the effect of an operating regulation is computed on the following basis:

- Vehicles below the limit are not affected.
- A percentage of those above the limit are assumed to be modified by retrofit. The remainder above the limit are left alone, with a reduced distribution proportional to the original shape.
- Retrofitted vehicles are brought approximately into compliance, forming a small distribution above the limit. For a noise limit of L, it is assumed

that 50 percent fall in the range L −1 dB to L, and 25 percent each in the ranges L −2 dB to L −1 dB and L to L +1 dB.*

Figures 17 and 18 show L^{eq} as a function of operating limits, for various degrees of compliance, for trucks operating at low and high speeds, using measured noise distributions from Reference 4. The original L^{eq} (i.e., before any regulation) is indicated by the dashed lines. The percent compliance refers to the percentage of those vehicles originally above the operating limit which are retrofitted.

Several key features are apparent in Figures 17 and 18:

- The resultant L^{eq} is not necessarily equal to the operating limit, but depends on the degree of compliance, and also on the relationship between the operating limit and the distribution. If most vehicles are below the limit they will not be affected by it. In such cases L^{eq} is usually less than the limit.
- L^{eq} is approximately equal to the limit when most of the original distribution is above the limit (so that most vehicles are modified to meet the limit) and there is 100 percent compliance.
- Compliance becomes increasingly more important as more stringent operating limits are introduced.

3.3.2 New Vehicle Standards

The effect of a new vehicle standard is that since the L^{eq} of new vehicles is less than that of old, the total fleet L^{eq} diminishes as old vehicles are replaced with new. The distribution of new vehicles is, within the present study, computed on the following basis:

- There is a population of new vehicles below the limit which is distributed the same way as the existing vehicles below the limit. This follows from

* It is expected that there will be some spread in the noise levels of retrofitted vehicles, although there is no data available as to the actual distribution. The distribution used here was chosen somewhat arbitrarily, based on the assumptions that retrofit measures will be intended to achieve the operating limit, that there will be some spread, and that some tolerance for measurement error will be permitted.

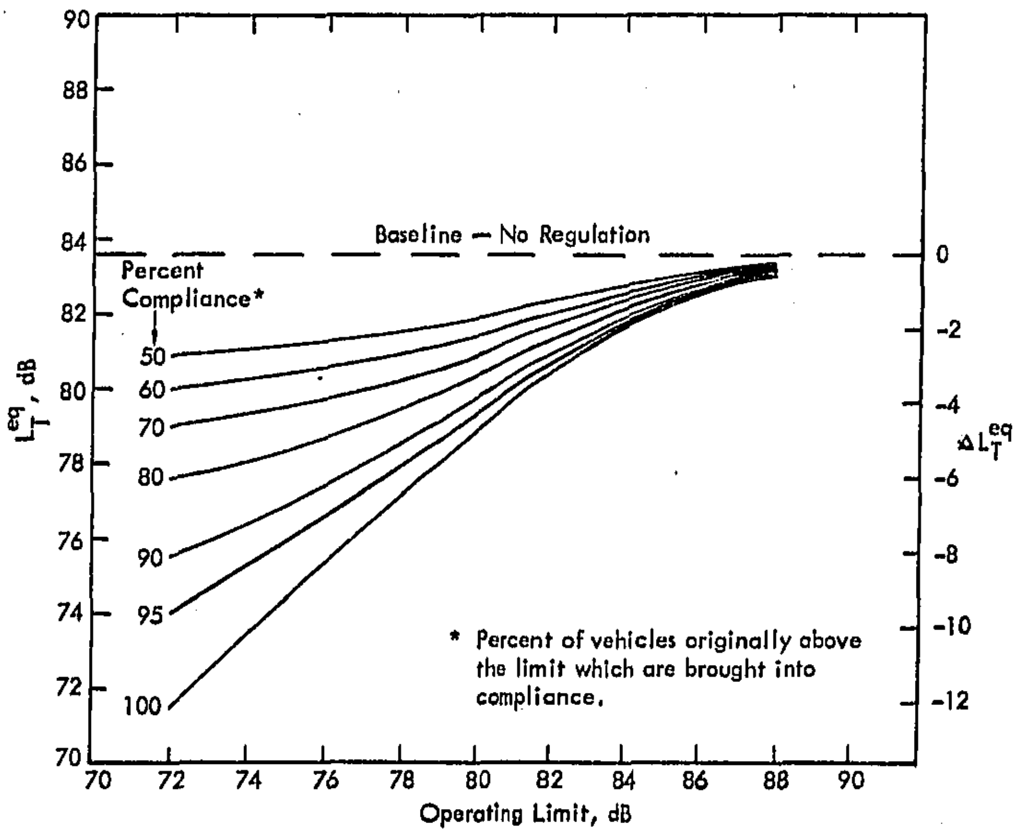

Figure 17. Effect of Operating Limit on L_T^{eq} at Low Speeds

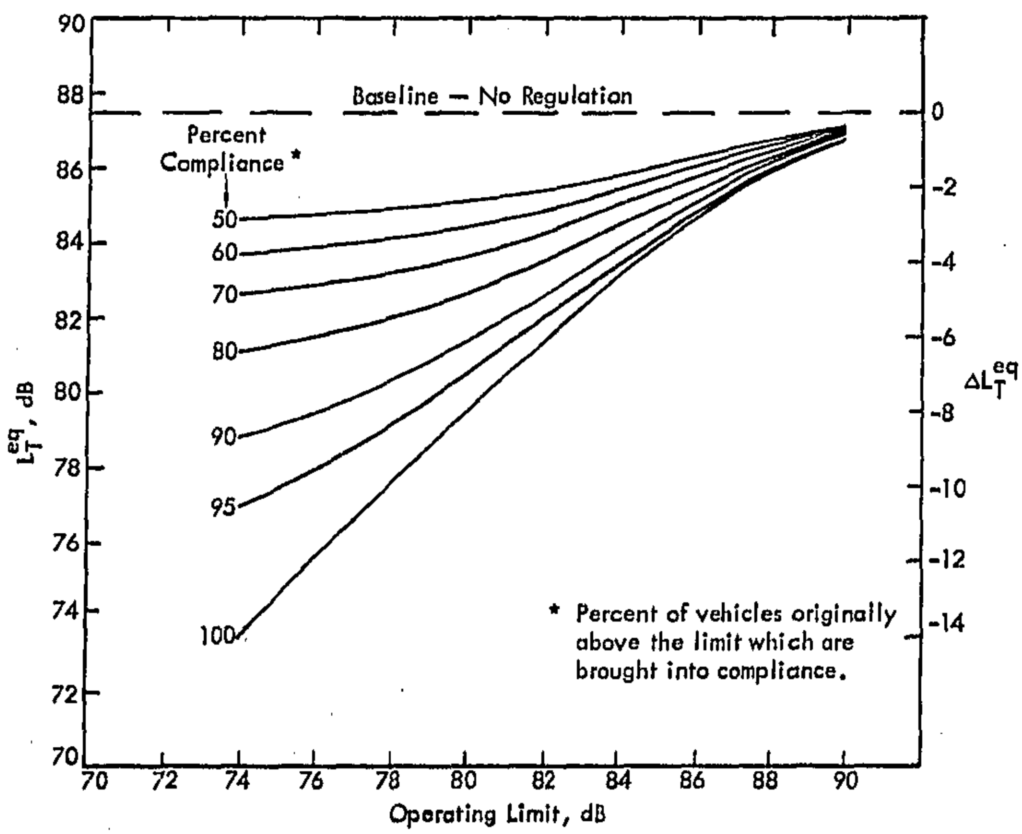

Figure 18. Effect of Operating Limit on L_T^{eq} at High Speeds

the steady-state assumption that if there were no regulations the new vehicle distribution would be the same as the existing one.

- New vehicles which would have been above the limit are modified in design so as to be brought into compliance. These vehicles are assumed to form a 25 percent–50 percent–25 percent distribution about the limit, just as with an operating limit.

Figure 19 shows the effect of this distribution change on L_T^{eq} at low speeds for the truck noise distribution shown in Figure 1. Shown is the value for new vehicles, denoted L_{new}^{eq}, as a function of the new vehicle limit. Note that L_{new}^{eq} in general does not equal the new vehicle limit, but is usually somewhat less.

The noise of the vehicle fleet in use is reduced in time as quieter new vehicles replace old. Figure 20 shows a generalized representation of this time-dependent reduction. Shown is ΔL^{eq} versus time (in years) for L_{new}^{eq} being less than the baseline L^{eq} by various amounts. The time-dependent calculation shown in Figure 20 is based on annual new vehicle sales being 10 percent of existing fleet size. This is consistent with historical experience for trucks,[19,20] and with automobile sales projections in Reference 10.

Consider a new vehicle standard of 80 dB for trucks at low speed. From Figure 19, $L_{new}^{eq} = 78.9$ dB. The new vehicle L^{eq} re: baseline is -4.7 dB; this case is shown in Figure 20. After 5 years, L_T^{eq} is reduced by slightly more than 1 dB. A reduction of 3 dB takes about 15 years.

The main feature seen in Figure 20 is that new vehicle standards take time to have an effect. Even after 30 years, L^{eq} falls somewhat short of the new vehicle L^{eq}. Even for unreasonably large reductions (i.e., the $\Delta L_{new}^{eq} = -50$ dB curve), a 3 dB reduction would be seen only after half the existing fleet retired, which takes 6 to 7 years. Coupled with the growth noted in Section 2.0, it is clear that new vehicle standards, if required, must be implemented with as little delay as possible.

3.3.3 Combined Regulations

Any actual regulation scenario will consist of a combination of operating limits and new vehicle standards. Operating limits can provide immediate benefits if reasonable and if enforced; new vehicle standards provide for introduction of that new technology

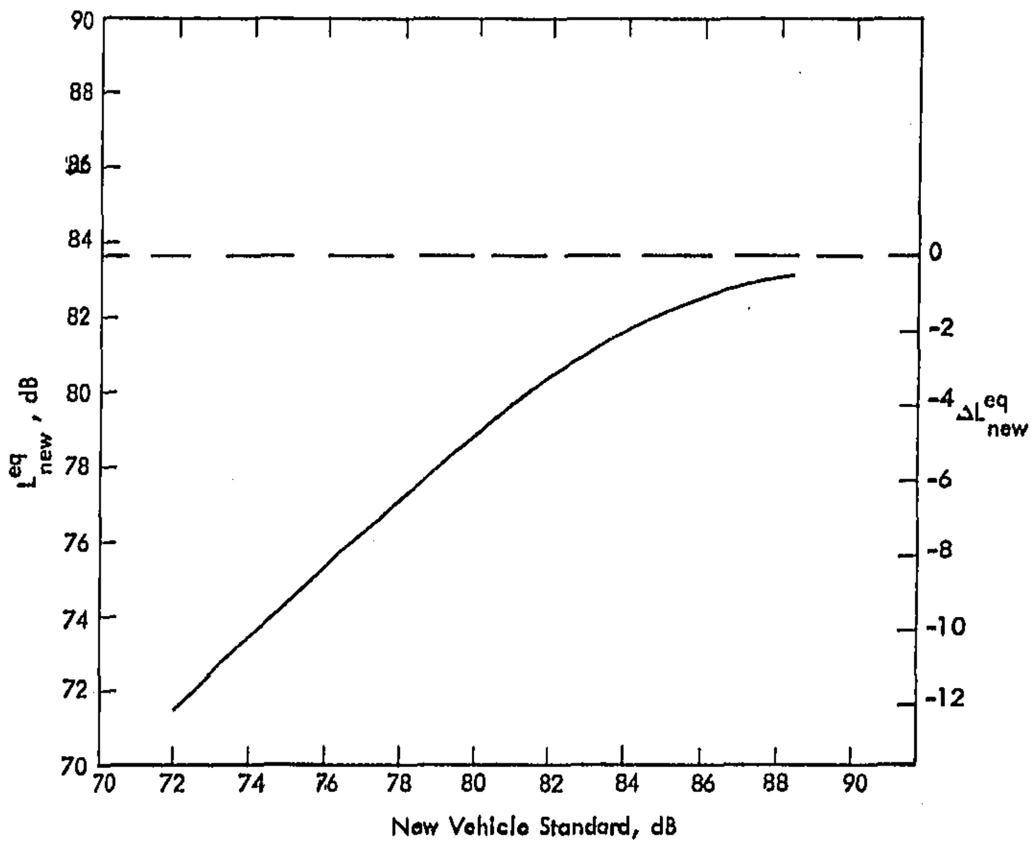

Figure 19. Effect of New Vehicle Standard on L^{eq} of New Trucks at Low Speeds

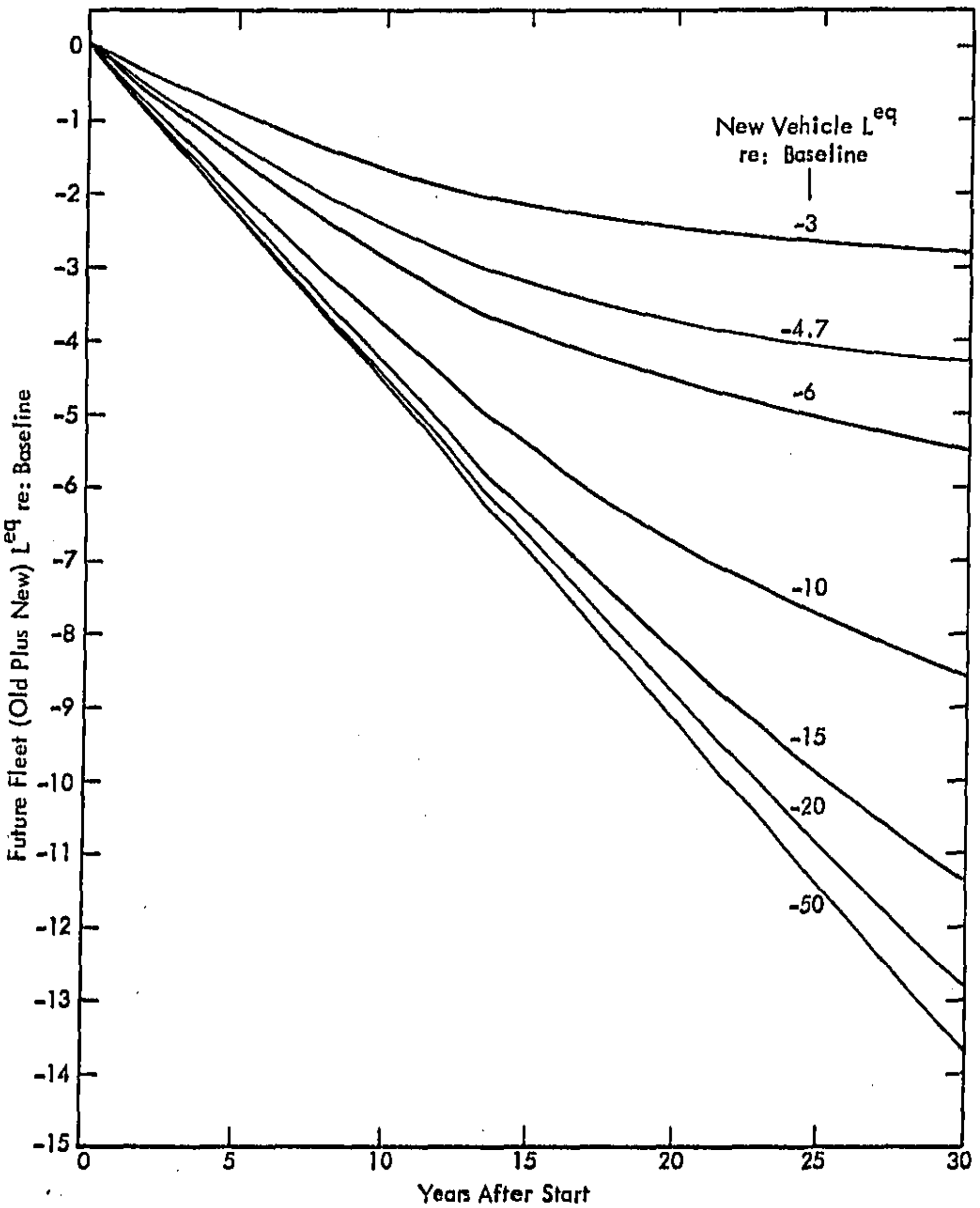

Figure 20. Effectiveness of New Vehicle Standard, With New Vehicle Sales Equalling 10 Percent of Fleet Size.

which may not be amenable to retrofit of existing vehicles, but take a long time to show an effect. A combined control plan, which must be dynamic in nature as noted earlier, would include systematically lower limits. New vehicle standards would be periodically lowered as available technology improves. Operating limits would also be periodically lowered to provide a basis for ensuring that originally quiet vehicles do not deteriorate and to take advantage of technology advancements suitable for retrofit, and also to help eliminate the last few old noisy vehicles after a new vehicle standard has been in effect for some time.

The specific effects of the two regulation types may be seen in Figure 9, where each regulation scenario contains both types. There is an immediate benefit in 1974-1975 when the motor carrier regulations took effect, and in 1985 for the assumed improved Motor Carrier scenario. The new vehicle standards, effective in 1978, 1982, and 1985, serve to reduce the growth rate of exposure. There is a change in slope of the regulation scenarios at these years. More complex examples are shown in Reference 1, with several stages of each regulation type.

4.0 CONCLUSIONS

A study of road noise exposure and vehicle noise reduction options has been conducted. Noise exposure was computed on the basis of actual traffic and population data in ten sample cities, projected to national totals. Population and vehicle growth were included, so that the study provides predictions for the period from 1970 through 2000. The following conclusions have been reached:

1. In 1970 (baseline year for this study) 17.6 million people were exposed to urban road traffic noise levels of $L_{dn} \geq 65$ dB.

2. Most exposure to highway noise in 1970 $L_{dn} \leq 70$ dB is from low-speed urban roads, and is dominated by truck noise. Most exposure to $L_{dn} \geq 70$ dB is due to high-speed urban roads. Exposure is greatest in large cities; rural exposure in 1970 is very small compared to the national total; this is expected to be the case in 2000.

3. With existing EPA truck noise regulation, the number of people exposed to $L_{dn} \geq 65$ dB in 2000 will be 23 percent greater than in 1970. The percentage of total population exposed will diminish slightly. Without regulations, the number of people exposed would have nearly doubled.

4. If a 75 dB (low speed) new truck standard is adopted in 1985, the number of people exposed to $L_{dn} \geq 65$ dB in 2000 will be about the same as in 1970. The percentage of total population exposed will decrease by 24 percent.

5. Driveline source controls alone have their greatest effect at low speeds; benefit at high speeds is minimal because of tire noise.

6. The existing Motor Carrier regulations will reduce population exposed to $L_{dn} \geq 65$ dB from high-speed urban traffic by about 10 percent (relative to no regulation), and the total exposure by less than 5 percent. A 45 mph truck speed limit in urban areas would provide a similar benefit.

7. The potential benefit of automobile noise reduction depends on truck noise levels. As trucks become quieter, the relative importance of automobiles will increase. With current truck levels, quieting automobiles would have

little benefit. In the year 2000, assuming only current truck regulations, exposure to $L_{dn} \geq 65$ dB from low-speed roads can be approximately halved (relative to exposure if automobiles stay as they are) if automobiles were to be completely silenced.

8. To realize a significant portion of the benefits from truck regulations, automobile noise levels must not be allowed to increase. A 2 dB increase in automobile noise levels (which could result from a shift to small cars, including diesels) in 2000 would negate the benefit of a 75 dB new truck standard.

9. Operating limits give an immediate reduction to noise exposure, but must be periodically lowered if exposure is not to increase subsequently in a growing traffic system. Enforcement can be a major factor in determining the effectiveness of an operating limit. New vehicle standards (which can specify a lower level than feasible for an operating limit) show an effect only after some time.

10. If significant reduction to traffic noise exposure is desired (e.g., reduce the exposure by half or more from the 1970 exposure), then automobile noise levels must be reduced, in addition to the truck noise regulations considered in this study. For a given goal, there are limited trade-offs between automobile and truck noise reductions. To achieve significant reductions in high-speed noise exposure, tire noise must be reduced. Exposure from high-speed roads, in particular, will increase if tire noise levels remain as they presently are.

11. Continued reductions in both driveline and tire noise are required to prevent reescalation of noise exposure as both population and fleet size increase.

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APPENDIX A

Barriers as a Noise Abatement Technique

In addition to vehicle source reduction as discussed in the body of this report, highway noise control can in principle be achieved by traffic management, adjustment of roadway location, land-use planning, etc. Very often the only method feasible in a given case is to construct barriers. Design procedures have been widely circulated by FHWA, and federal funding is available for approved projects. Barriers are currently being constructed near noise-sensitive areas along federally funded highway projects.

In order to evaluate the potential effectiveness of barriers to reduce the national exposure to highway noise, a calculation has been performed of the noise exposure from federally funded highways, and of the potential benefits of using barriers alone as an abatement technique. The calculation is limited to federal-aid highways because these are the ones for which funding is generally available. Vehicle noise limits are not included in this calculation. As shown in the body of this report, existing regulations have very little benefit at high speeds; the roads considered in this Appendix are primarily high speed.

The calculations in this Appendix are based on actual distributions of road mileage and traffic volume, but do not utilize the detailed population model described in the body of this report. The criteria used to select the ten sample cities did not include systematic representation with regard to federal-aid highways. Collection of additional population data for an appropriate sample was not warranted, however, in view of the somewhat qualitative nature of the present calculation. A single average urban population density has been used. This density is based on the median of the population distribution of urban areas.

A.1 Traffic on Federally Funded Highways

Table A-1 shows the traffic on federally funded highways, in terms of the numbers of miles of highway with a given average daily traffic (ADT). There are four main systems: urban interstate, urban primary, rural interstate, and rural primary. Data for ADT up to 40,000 are from Reference A-1; distributions above this value are extrapolated within the constraint that total road and vehicle mileage are consistent with values given in

Table A-1

Traffic on Federal-Aid Highways (1974)[A-1]

	Miles of Road			
ADT (Thousands)	Urban Interstate	Urban Primary*	Rural Interstate	Rural Primary *
<0.4	38	242	83	8,610
0.4-1	2	223	448	32,259
1-2	23	858	1,756	50,386
2-3	31	1,267	2,511	33,911
3-4	82	1,573	2,788	21,064
4-5	137	1,520	3,075	12,895
5-10	902	7,556	11,077	21,115
10-15	1,076	5,391	6,364	4,373
15-20	1,093	3,424	2,834	1,318
20-30	1,742	3,253	2,059	705
30-40	1,129	1,109	472	122
40-60	1,100	660	204	48
60-80	840	450	--	--
80-100	600	335	--	--
100-120	125	--	--	--
120-150	70	--	--	--

*Excluding Interstate.

Table A-2

Road and Traffic Parameters

	Urban Interstate	Urban Primary	Rural Interstate	Rural Primary
Speed (mph)	55	35	55	55
Percent Trucks[A-2]	8.7	3.4	15.6	8.2
Number of Lanes	8	4	4	2
Median Width (feet) *	0	0	50	0

* Median strip widths estimated here are the minimum which would normally be found on each type highway.

Reference A-1. Table A-2 gives roadway configuration, speed and the percentage of medium and heavy trucks for each type road. Truck percentages are from Reference A-2; other data in Table A-2 are assumed values typical of each type of road.

Traffic predictions for future years were also made. Table A-3 shows predicted traffic distributions for 2000. Future predictions in this analysis were made on the following basis:

- Total traffic (vehicle miles) increases at a rate of 2.3 percent per year. This is a composite value between the annual growths of 2.4 percent for trucks and 2.0 percent for automobiles used in the body of this report, and is consistent with estimates in References A-3 and A-4. It is appropriate to use a growth factor weighted toward trucks because they are the dominant noise source.
- Volume (ADT) on rural interstates increases at a rate of 3.8 percent per year, while road mileage remains approximately fixed. This is based on data in Table I-1 of Reference A-3.
- Total volume and road mileage of rural primaries increase at approximately 0.5 percent per year. This is based on the "full needs" case in Table I-1 of Reference A-3.
- Mileage of urban primary roads is assumed to increase at a rate of 1 percent per year, the rate of growth of the population. This is consistent with the growth model used in the body of this report.
- Urban interstate mileage is fixed at approximately 9,000 miles.
- Traffic mix is the same as present.

A.2 Noise Exposure From Federally Funded Highways

The noise exposure from these highways has been computed on the following basis:

- Distance to L_{dn} = 60, 65, 70, and 75 dB contours were computed for each ADT range using the method of Reference A-5. This model includes lane-by-lane detail which is important for barrier calculation.

Table A-3

Projected Traffic on Federal-Aid Highways in 2000

ADT (Thousands)	Miles of Road			
	Urban Interstate	Urban Primary*	Rural Interstate	Rural Primary*
<0.4	7	224	31	9,802
0.4-1	6	241	47	36,726
1-2	14	614	284	59,639
2-3	12	869	421	38,606
3-4	17	1,172	665	23,981
4-5	24	1,398	665	14,680
5-10	290	7,035	4,894	24,039
10-15	494	6,588	5,177	4,978
15-20	528	4,986	4,196	1,500
20-30	1,164	6,033	7,106	803
30-40	1,138	3,009	4,714	139
40-60	1,827	2,169	3,267	55
60-80	1,102	611	1,574	--
80-100	1,167	333	1,358	--
100-120	591	374	100	--
120-150	545	308	--	--
150-200	173	--	--	--
200-300	67	--	--	--

*Excluding Interstate.

- The distance to each contour, less an assumed 50-foot (15-meter) setback distance, was multiplied by the number of miles of road carrying each ADT, then by two, to obtain area exposed on both sides of the road.
- The number of people exposed was then obtained by multiplying the area by 4,500 people per square mile (1,737 per square km) in urban areas (this is the median value of density in Table 1) and 56 people per square mile (22 per square km) in rural areas (total U.S. population divided by total U.S. area).

Table A-4 summarizes the calculated exposure for 1974* for the four road types. Note that the total exposure is much less than the national total calculated from the ten-city model (see Figure 10 and Appendix D). This is because most urban primary roads are not federal aid. The urban interstate exposure accounts for most of the urban high-speed noise. An exact comparison between the two calculations is not possible, however, because this calculation uses a representation of population greatly simplified as compared to that used in the body of this report. This simplified calculation would tend to underpredict exposure to high levels.

Table A-5 shows the exposure in 2000 for the four systems. Figure A-2 shows exposure to $L_{dn} \geq 60$, 65, 70, and 75 dB as a function of time for the urban interstate system. The growth characteristics of exposure are similar to those discussed in general in the body of this report.

A.3 Barriers on Urban Interstate Highways

The noise abatement potential of barriers has been evaluated by calculating reduced exposure for several scenarios. The calculations are limited to urban interstates. Rural highways are not included because their total exposure is small compared to urban. Urban primary roads are not included because barriers are rarely practical on them due to cross-streets, need for access, etc.

Tables A-6 and A-7 show the distribution of noise exposure in 1974 and 2000 for no barriers and for 10-foot (3-meter), 15-foot (4.5-meter), and 20-foot-high (6-meter)

* The most recent year for which traffic and highway statistics were available at the time of this calculation.

Table A-4

Area (Square Miles) and People* (Millions) Exposed to Noise From Federally Funded Highways in 1974

	L_{dn} Exceeded							
	60		65		70		75	
Road System	Area	People	Area	People	Area	People	Area	People
Urban Interstate	3,033	13.6	1,216	5.5	337	1.5	79	0.36
Urban Primary**	1,590	7.2	431	1.94	54	0.24	1	0.005
Rural Interstate	5,130	0.29	2,238	0.13	565	0.032	51	0.003
Rural Primary**	8,871	0.50	2,255	0.13	364	0.020	14	0.001

*People impacted based on 4500 people/mi^2 in urban areas and 56 people/mi^2 in rural areas.

**Excluding Interstate.

Table A-5

Area (Square Miles) and People* (Millions) Exposed to Noise From Federally Funded Highways in 2000

	L_{dn} Exceeded							
	60		65		70		75	
Road System	Area	People	Area	People	Area	People	Area	People
Urban Interstate	4,682	21.1	1,964	8.8	696	3.1	197	0.87
Urban Primary**	2,814	12.7	809	3.6	136	0.61	12	0.05
Rural Interstate	13,154	0.74	5,724	0.32	1,954	0.11	488	0.03
Rural Primary**	10,174	0.57	2,487	0.14	418	0.023	16	0.001

*People impacted based on 4500 people/mi^2 in urban areas and 56 people/mi^2 in rural areas.

**Excluding Interstate.

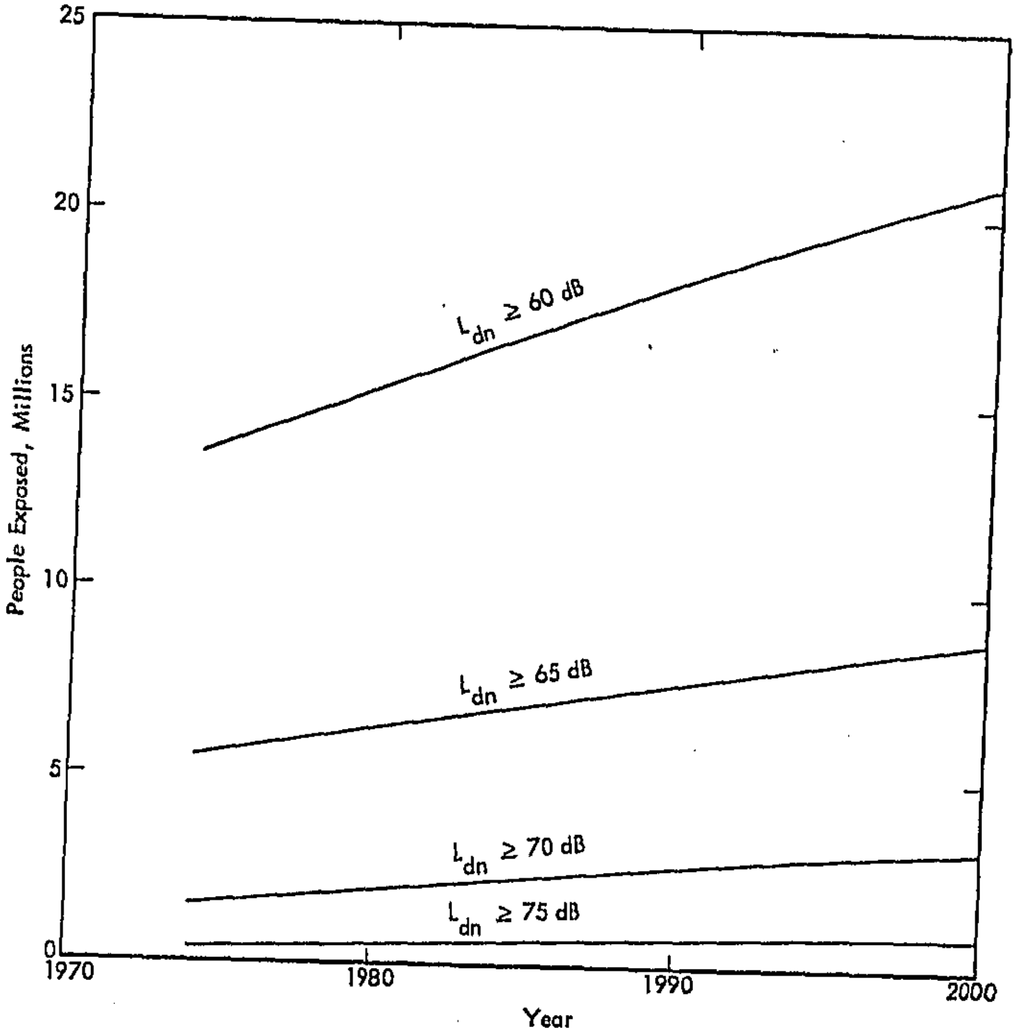

Figure A-1. Numbers of People Exposed to Noise from Urban Interstates, 1974-2000.

Table A-6

Distribution of Areas Exposed to Noise from Urban Interstates in 1974 for Several Barrier-Heights

Average Daily Traffic (ADT)	Miles of Road	Distance (Feet) From Center of Outer Lane to L_{dn} Contour,* No Barrier				Exposed Area, Square Miles															
						No Barrier				10 ft (3m) Barrier				15 ft (4.5m) Barrier				20 ft (6m) Barrier			
		60	65	70	75	60	65	70	75	60	65	70	75	60	65	70	75	60	65	70	75
<400	38	---	---	---	---	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
400-1K	2	---	---	---	---	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-2K	23	84	---	---	---	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2-3K	31	138	---	---	---	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3-4K	82	180	70	---	---	4	0.6	0	0	2.3	0	0	0	0	0	0	0	0	0	0	0
4-5K	137	219	80	---	---	8.8	1.6	0	0	5.1	0	0	0	0	0	0	0	0	0	0	0
5-10K	902	310	135	---	---	88	29	0	0	71.3	0	0	0	0	0	0	0	0	0	0	0
10-15K	1,076	450	195	72	---	163	59	8	0	150	26	0	0	14.6	0	0	0	0	0	0	0
15-20K	1,093	600	245	93	---	227	80	17	0	227	53	0	0	33	0	0	0	14	0	0	0
20-30K	1,742	800	325	125	50	494	181	49	0	494	141	0	0	92	3	0	0	92	0	0	0
30-40K	1,129	1,050	430	172	68	427	162	52	7	427	148	18	0	94	12	0	0	67	0	0	0
40-60K	1,100	1,350	590	230	94	541	225	75	18	541	223	41	0	137	32	0	0	108	13	0	0
60-80K	840	1,650	740	300	120	509	219	79	22	509	219	62	0	141	38	0	0	120	21	0	0
80-100K	600	1,800	880	350	150	397	188	68	22	397	188	54	0	113	37	1.8	0	99	24	0	0
100-120K	125	2,300	1,000	420	185	106	44	17	6	106	44	15	2.5	32	9	1.3	0	27	5	0	0
120-150K	70	2,600	1,100	520	220	67	27	12	4	12	27	26	10	20	6	1.5	0	18	4.7	0.4	0

Table A-7

Distribution of Areas Exposed to Noise from Urban Interstates in 2000 for Several Barrier Heights

Average Daily Traffic (ADT)	Miles of Road	Distance (Feet) From Center of Outer Lane to L_{dn} Contour, No Barrier				Exposed Area, Square Miles															
						No Barrier				10 ft (3m) Barrier				15 ft (4.5m) Barrier				20 ft (6m) Barrier			
		60	65	70	75	60	65	70	75	60	65	70	75	60	65	70	75	60	65	70	75
<400	7	---	---	---	---	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
400-1K	6	---	---	---	---	0	0	0.	0	0	0	0	0	0	0	0	0	0	0	0	0
1-2K	14	84	---	---	---	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2-3K	12	138	---	---	---	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3-4K	17	180	70	---	---	0.8	0.1	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0
4-5K	24	219	80	---	---	1.5	0.3	0	0	0.9	0	0	0	0	0	0	0	0	0	0	0
5-10K	290	310	135	---	---	28.5	9.3	0	0	23	0	0	0	0	0	0	0	0	0	0	0
10-15K	494	450	195	72	---	74	27	4.1	0	69	12.9	0	0	6.7	0	0	0	0	0	0	0
15-20K	528	600	245	93	---	110	39	8.6	0	110	25.7	0	0	16	0	0	0	6.8	0	0	0
20-30K	1,164	800	325	125	50	330	121	33	0	330	94	0	0	61	2.5	0	0	61	0	0	0
30-40K	1,138	1,050	430	172	68	431	163	52	7	431	150	18	0	94	12	0	0	68	0	0	0
40-60K	1,827	1,350	590	230	94	899	373	124	30	899	370	68	0	227	53	0	0	179	22	0	0
60-80K	1,102	1,650	740	300	120	667	287	104	29	667	287	82	0	184	49	0	0	157	14	0	0
80-100K	1,167	1,800	880	350	150	773	336	132	44	773	366	106	0	220	73	3.5	0	193	46	0	0
100-120K	591	2,300	1,000	420	185	503	212	62	30	503	212	70	11	151	42	6.3	0	127	23	0	0
120-150K	545	2,600	1,100	520	220	526	216	97	35	526	216	21	20	157	48	11.4	0	145	36	2.9	0
150-200K	173	3,500	1,600	660	280	226	101	39	15	226	101	39	11	65	62	6.6	0	65	22	3.6	0
200-300K	67	4,500	2,000	840	360	112	49	20	7	112	49	20	6	29	26	3.9	0	29	13	3.4	0

barriers.* Barriers higher than 20 feet (6 meters) would give little or no additional benefit. Shown for each ADT range are the distances to the L_{dn} = 60, 65, 70, and 75 dB contours with no barriers, and the areas exposed for no barriers and for the three height barriers. The barrier calculations were performed using the method of Reference A-6, assuming level terrain and placing barriers 25 feet (7.5 meters) to each side of the road.

Four barrier-use scenarios have been considered, each with the goal of eliminating (where feasible) exposure to L_{dn} above a given value. These are:

- Eliminate exposure to $L_{dn} > 75$ dB. This requires construction of 15-foot barriers where ADT > 100K, and 10-foot barriers where 30K < ADT < 100K.
- Eliminate exposure to $L_{dn} \geq 70$ dB. This requires 20-foot barriers where ADT > 80K, 15-foot barriers where 30K < ADT < 80K, and 10-foot barriers where 10K < ADT < 30K.
- Eliminate exposure to $L_{dn} \geq 65$ dB. This requires 20-foot barriers where ADT > 20K, 15-foot barriers where 10K < ADT < 20K, and 10-foot barriers where 3K < ADT < 10K.
- Eliminate exposure to $L_{dn} \geq 60$ dB. This requires 20-foot barriers where ADT > 10K, 15-foot barriers where 3K < ADT < 10K, and 10-foot barriers where 1K < ADT < 3K.

Tables A-8 and A-9 show the number of miles of each height barrier, and the exposure for each scenario, in 1974 and 2000. Note that the goal of each scenario is not necessarily achieved because of the limit of effectiveness of barriers limited to a practical height of no more than 20 feet. The goals might more properly be stated "eliminate to the extent feasible", rather than "eliminate".

Figure A-2 shows the 1974 exposure data from Table A-8 in graphical form. The first application of barriers (Scenario A) has its greatest effect at high-noise levels. The other scenarios, with more extensive barriers, tend to shift the distribution downward, with a residual tail at high levels which cannot be eliminated with barriers.

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* Only these three heights were considered in the calculations and in the ensuing discussion. Equivalent reduction to exposure could be achieved in some cases with lower barriers, e.g., 15-foot barriers are assumed here in places where ones greater than 10 feet but less than 15 feet would suffice.

Table A-8

Noise Exposure From Urban Interstates in 1974
for Several Barrier Scenarios

Scenario	Miles of Barriers			People Exposed to Greater L_{dn} (Millions)			
	10'	15'	20'	60 dB	65 dB	70 dB	75 dB
Baseline – No Barrier	0	0	0	13.6	5.5	1.5	0.36
A – Eliminate L_{dn} ≥ 75 dB	7,338	390	0	13.1	5.1	1.1	0
B – Eliminate L_{dn} ≥ 70 dB	7,822	6,138	1,590	6.7	1.7	0.002*	0
C – Eliminate L_{dn} ≥ 65 dB	2,242	4,338	11,212	3.0	0.31*	0.002	0
D – Eliminate L_{dn} ≥ 60 dB	108	2,242	15,550	2.5*	0.31	0.002	0

* Not feasible to eliminate completely exposure with barriers.

Table A-9

Noise Exposure From Urban Interstates in 2000
For Several Barrier Scenarios

Scenario	Miles of Barriers			People Exposed to Greater L_{dn} (Millions)			
	10'	15'	20'	60 dB	65 dB	70 dB	75 dB
Baseline — No Barriers	0	0	0	21.1	8.8	3.1	0.87
A — Eliminate L_{dn} ≥75 dB	10,468	2,752	0	16.7	7.0	1.6	0
B — Eliminate L_{dn} ≥70 dB	4,372	8,134	5,086	7.2	1.8	0.045*	0
C — Eliminate L_{dn} ≥65 dB	662	2,044	15,548	4.8	0.79*	0.045	0
D — Eliminate L_{dn} ≥60 dB	52	662	17,592	4.6*	0.79	0.045	0

* Not feasible to eliminate completely exposure with barriers.

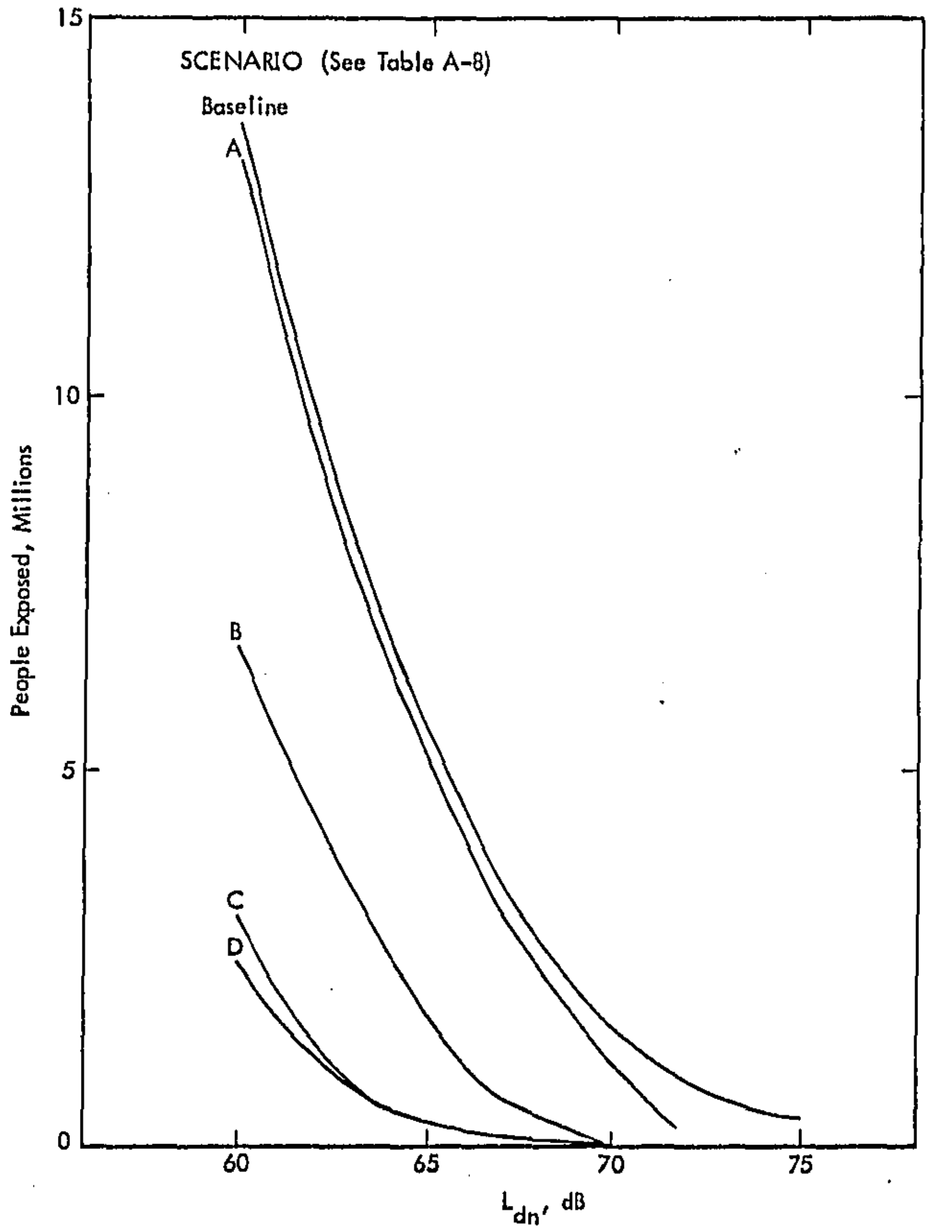

Figure A-2. Changes in Noise Exposure from Urban Interstates in 1974 for Four Barrier Scenarios.

Figure A-3 shows the effect of barriers on the total national exposure as computed in the body of this report. Shown are the total national exposure (in 1974), the exposure from low-speed roads alone, and reduced total exposure associated with the four barrier scenarios. The reduced exposures were obtained by applying the reductions shown in Figure A-2 to the "Total Baseline" distribution shown in Figure A-3. The overall effect of barriers on total highway noise exposure is seen. The barriers cause the distribution of exposure to shift from the original total toward the low-speed-only distribution. The transition takes place more at high noise levels than at low.

It should be noted from Tables A-8 and A-9 that the application of barriers considered here is extensive. Scenario A, the least extensive application, involves barriers on both sides of nearly half the urban interstates in 1974 and nearly three-quarters in 2000. A practical application of barriers would have an effect between "Baseline" and "A" as shown in Figure A-2. The benefit of barriers (considered on a national scale) is limited to worst-case situations as a realistic alternative to source control or use restriction, and has little effect on the national exposure.

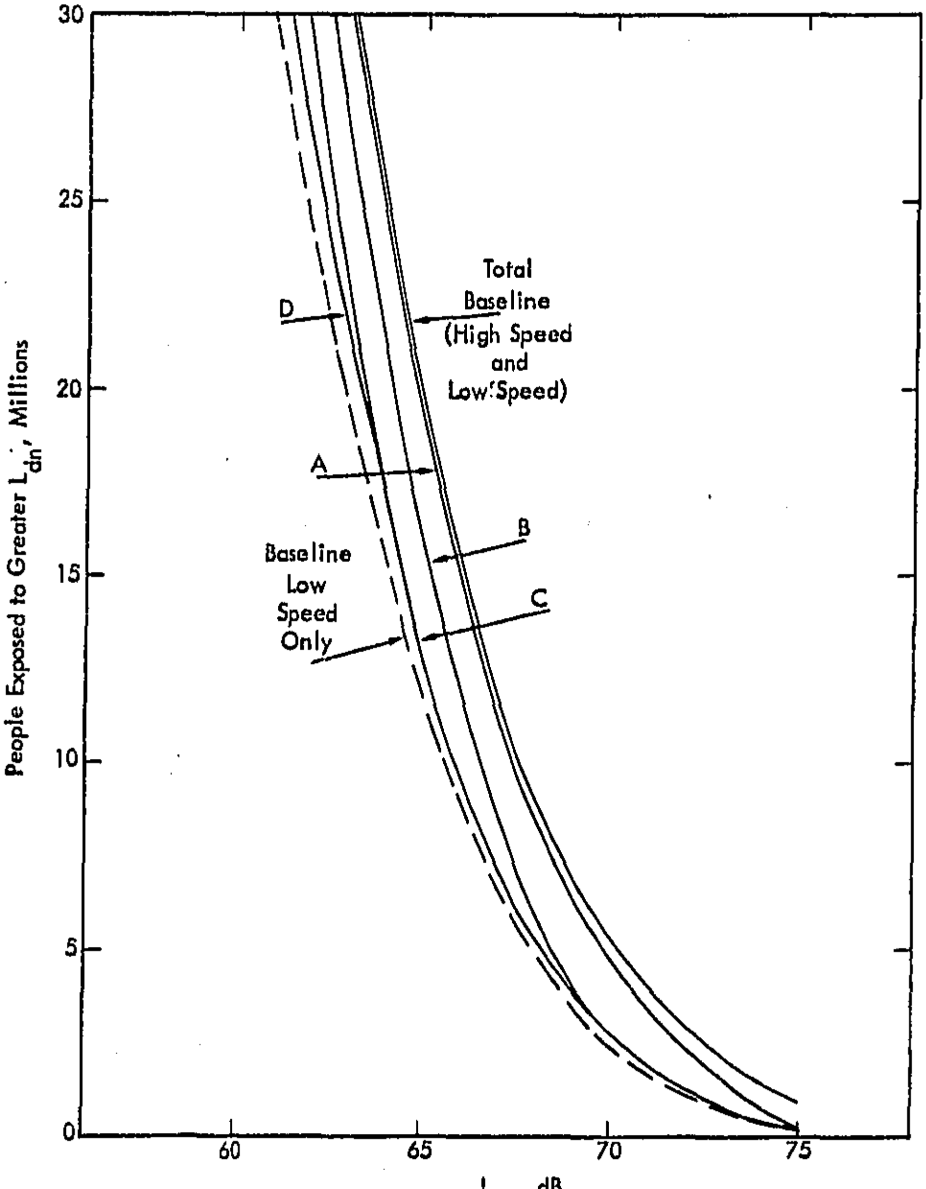

Figure A-3. Changes in Total National Noise Exposure in 1974 for Four Barrier Scenarios on Urban Interstates.

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A-1. "Highway Statistics 1974", Highway Statistics Division, Office of Highway Planning, Federal Highway Administration.

A-2. Kent, P., and Bishop, H., "1974 National Truck Characteristic Report", Planning Services Branch, Office of Highway Planning, Federal Highway Administration, April 1974.

A-3. "Interagency Study of Post-1980 Goals for Commercial Motor Vehicles" (Draft), June 1976.

A-4. "The Report by the Federal Task Force on Motor Vehicle Goals Beyond 1980" (Draft), September 2, 1976.

A-5. Plotkin, K. J., "A Model for the Prediction of Highway Noise and Assessment of Strategies for Its Abatement Through Vehicle Noise Control", Wyle Research Report WR 74-5, September 1974.

A-6. Sharp, B. H., Plotkin, K. J., Glenn, P. K., and Slone, R. M., "A Manual for the Review of Highway Noise Impact", Wyle Research Report WR 76-24, May 1977. Also, EPA Report 550/9-77-356.

APPENDIX B

Computer Programs

The impact of future traffic noise presented in this study was accomplished using a system of three computer programs. The divisions among the three were at natural points indicated in the body of this report, and permitted significant economy of calculation for alternate scenarios. The three programs are described in the following subsections. Their interrelationship is shown in Figure B-1, and is discussed in Section B.4.

B.1 Ten-City Noise Impact Model (TECNIM)

This program performs the detailed calculation discussed in Sections 1.1 and 2.2. Basic input data consist of that listed in Section 2.2.1. Altered vehicle noise levels are specified as ΔL^{eq}. For a given set of ΔL^{eq}'s (automobiles and trucks, low and high speed), TECNIM computes the number and fraction of people exposed to the L_{eq} bands of 55-60, 60-65, 65-70, 70-75 and 75-80 dB. Distributions of exposure to L_{dn} are obtained by shifting the distributions by 3.3 dB, as discussed in Section 2.2.3.

TECNIM is written in general form, so that impact may be computed in any city for which traffic and population data have been prepared. For the present study, dimensions and input/output are keyed to the ten sample cities. A loop structure is incorporated to obtain impact calculations for ΔL_A^{eq} from +3 to -15 dB, and ΔL_T^{eq} from +3 to -16 dB. The impact distributions are written on a data file which is then read by REGIM.

B.2 Regulation Impact Model (REGIM)

This program reads the impact vs. ΔL^{eq} data prepared by TECNIM, and applies the population statistics discussed in Section 2.3, and vehicle-use data discussed in Section 2.4, to obtain future impact. User inputs to the program are the year and the four ΔL^{eq}'s. REGIM contains all growth factors. Vehicle-use growth is treated as an equivalent increase to L^{eq}. For example, a doubling of per capita vehicle mileage is equivalent to ΔL^{eq} = +3 dB. The program combines this "growth" ΔL^{eq} with the input ΔL^{eq} to an effective net value for computational purposes. Output is the distribution of noise impact, as discussed earlier.

REGIM is operated conversationally on the IBM 370 CMS system. Input parameters may be specified on a case-by-case basis, or may be read from a data file prepared by HINCSAM.

B.3 Highway Noise Control Strategy Assessment Model (HINCSAM)

This program, described fully in Reference B-1, performs the calculations described in Sections 1.2 and 3.3. Inputs are the existing vehicle distribution and a sequence of regulations. Output is L^{eq} as a function of time for the specified regulation scenarios.

B.4 Combination of Models

Figure B-1 shows the relationship among the models in the complete software package. REGIM accepts the impact vs. ΔL^{eq} data created by TECNIM, growth data, and ΔL^{eq}'s to provide national noise impact. The ΔL^{eq}'s may be specified arbitrarily in order to obtain results as shown in Figures 10 through 13, or from a HINCSAM calculation to obtain a time history of impact for a given regulation scenario, as shown in Figures 8 and 9.

REFERENCE FOR APPENDIX B

B-1. Plotkin, K.J., "A Model for the Prediction of Highway Noise and Assessment of Strategies for its Abatement Through Vehicle Noise Control", Wyle Research Report WR 74-5, September 1974.

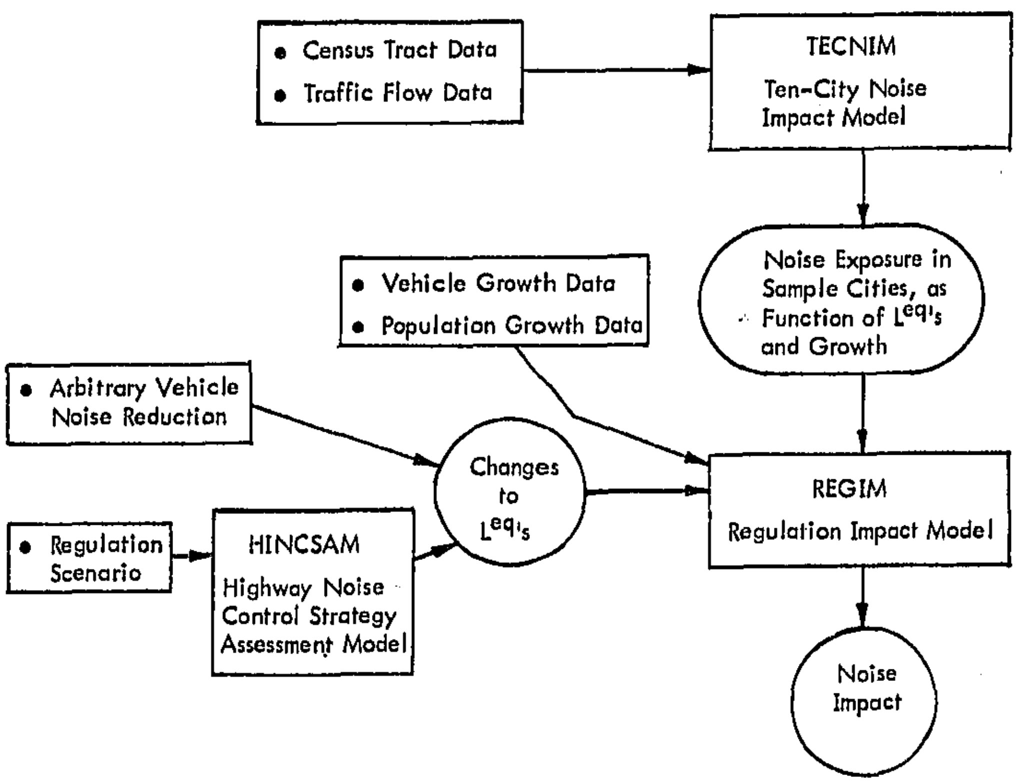

Figure B-1. Relation Among Programs in Software Package.

APPENDIX C

Estimate of Noise Levels Near Traffic Lights

The freely flowing assumptions of constant speed and constant vehicle noise source level are not valid near traffic lights. During deceleration from cruise speed, noise levels are generally lower than cruise levels. During acceleration to cruise speed, levels can be higher. During both phases, time duration is increased because the speed is less than cruise speed. Furthermore, noise contours will no longer be parallel to the road, but will have a curved shape dependent on specific vehicle behavior.

Calculation of actual noise contour shape near traffic lights requires detailed vehicle and traffic data not available at this time. For the purposes of the present study, an estimate of the effect of traffic lights has been made based on the following assumptions:

- Change in vehicle noise source level is combined with duration change to give an equivalent vehicle L^{eq} near traffic lights.
- Equivalent stop/go L^{eq} is averaged (on an energy basis) over the duration of the approach and departure from the traffic lights.
- Assuming that one-half the vehicles stop and the other half flow freely (50/50 split of light cycle), an average equivalent L^{eq} is obtained.
- Noise contours in the vicinity of traffic lights are computed using this average equivalent L^{eq}. The contours are parallel to the road, along a length based on constant acceleration to cruise speed.
- The number of traffic lights per mile is estimated on the basis of overall statistics of numbers of traffic lights and highway miles.

Quantitative details of the calculation of increased vehicle levels and traffic light occurrence are given in the following sections.

C.1. Vehicle Levels

If a vehicle undergoing typical acceleration exhibits noise level L(V) as a function of speed, then the average source level is given by

$$\langle L \rangle = 10 \log_{10} \frac{1}{T} \int_0^T 10^{L(V)/10} \, dt \qquad \text{(C-1)}$$

where T is the time period of the acceleration. The level L(V) is a function of acceleration rate and vehicle type.

Application of the quantity $\langle L \rangle$ as given by Equation (C-1) to the highway noise model requires using the average speed during the acceleration. If acceleration is constant between zero and cruise, then the average speed is half the cruise speed. If L^{eq} in Equation (1) is replaced by $\langle L \rangle$ as given by Equation (C-1), then the speed term $10 \log_{10} V$ becomes $10 \log_{10} V_{cruise} + 3$ dB. The duration correction may be combined with $\langle L \rangle$, so that the effective level of stop and go traffic is

$$\langle L \rangle_{SG} = 3\,\text{dB} + 10 \log_{10} \frac{1}{T} \int_0^T 10^{L(V)/10} \, dt \qquad \text{(C-2)}$$

Assuming a traffic signal has a 50/50 timing split, half the traffic stops and half the traffic cruises through the signal. For traffic near lights, then, the appropriate average equivalent level is

$$\langle L^{eq} \rangle_{SG} = 10 \log_{10} \tfrac{1}{2} \left[10^{L^{eq}/10} + 10^{\langle L \rangle_{SG}/10} \right] \qquad \text{(C-3)}$$

where L^{eq} is the cruise level and $\langle L \rangle_{SG}$ is as given by Equation (C-2).

Automobiles

Table C-1 gives speed dependent noise levels for automobiles undergoing typical deceleration to and acceleration from rest.[C1] The levels are relative to 35 mph cruise levels for the same vehicles. Based upon data presented in References C2 and C3, the typical acceleration rate from rest is 0.15g and the typical deceleration rate to rest is 0.17g. Applying these rates and the levels in Table C-1 to Equations (C-2) and (C-3) over a full stop/start cycle from 35 mph (56 km/h) cruise gives

Table G-1

Automobile Noise Levels
for Acceleration and Deceleration

Speed Range (mph)	Level Re: Cruise at 35 mph (56 km/h)					
	Low HP/Wt		Medium HP/Wt		High HP/Wt	
	Accel.	Decel.	Accel.	Decel.	Accel.	Decel.
0 - 5	-6.5	-11.0	-8.2	-13.2	-5.6	-9.1
5 - 10	-3.6	-9.7	-4.8	-11.6	-3.3	-9.1
10 - 15	+2.0	-7.9	-1.7	-9.4	-1.1	-9.1
15 - 20	+4.6	-6.1	+2.5	-7.2	+2.9	-9.1
20 - 25	+8.2	-4.4	+5.9	-5.2	+3.9	-5.6
25 - 30	+10.5	-2.5	+8.3	-3.1	+5.1	-3.3
30 - 35	+13.5	-0.8	+9.9	-1.0	+7.9	-0.8

$$\langle L_A^{eq} \rangle_{SG} = L_A^{eq} + \begin{cases} 2.6 \text{ dB}, & \text{high HP/wt} \\ 4.0 \text{ dB}, & \text{medium HP/wt} \\ 6.2 \text{ dB}, & \text{low HP/wt} \end{cases} \qquad \text{(C-4)}$$

For the purpose of this study, the average value of 4.5 dB increase in level has been used. The total distance covered at the deceleration and acceleration rates noted above is 507 feet. The increased noise levels are applied over this distance, on low-speed roads only.

Trucks

Truck noise measurements indicate that peak pass-by levels at low speeds are independent of speed, so that the second term of Equation (C-2) equals L_T^{eq}. The adjustment for trucks is thus limited to the first term, the 3 dB duration correction. Applying this to half the traffic, as above,

$$\langle L_T^{eq} \rangle_{SG} = L_T^{eq} + 1.8 \text{ dBA} \qquad \text{(C-5)}$$

This is applied over the same distance as for automobiles.

C.2 Traffic Light Occurrence

Statistical data[C4] indicates there is one traffic light per 900 people in urban areas. In the urban areas represented in this study there are thus 165,000 traffic lights.

The total low speed road mileage considered in the ten sample cities projects to 75,000 miles. This is a small fraction of the municipal total of 631,229 miles given in Reference C5. However, the total number of vehicle miles per year projected from the present study is approximately 10 percent less than the total urban vehicle-mile usage given in Reference C5. The 75,000 road miles treated by the data base thus accounts for 90 percent of urban traffic. The remainder is on local streets with low traffic volumes which do not contribute significantly to noise impact.

If it is assumed that all traffic lights are located at intersections of two of the major streets considered, there are an average of four lights per mile. If all lights are located at intersections of a major street with a minor street, there would be two lights per mile. For the present study, a value of three lights per mile (1.9 lights per km) has been assumed on low-speed roads. It should be noted that this represents an overall order of magnitude estimate which must be refined by a systematic review of traffic light usage as a function of population, road and traffic conditions.

REFERENCES FOR APPENDIX C

C1. Pataky, Paul P., General Motors Eastern Technical Center, Warren, Mich., Presentation at the United States Environmental Protection Agency Meeting On Automobile/Light Truck Noise Measurement Methodology, July 16, 1976.

C2. "Vehicle Operations Survey," CRC APRAC Project No. CAPE-10-68 (1-70), Scott Research Laboratories, Inc., San Bernadino, Calif., December 1971.

C3. Kruse, R.E., and Huls, T.A., "Development of the Federal Urban Driving Cycle," SAE Paper 730553, May 1973.

C4. Cass, Samuel, "Traffic Signals," Chapter 17, Transportation and Traffic Engineering Handbook, edited by John E. Baerwald, Prentice Hall, New Jersey, 1976.

C5. "Highway Statistics 1973," Highway Statistics Division, Office of Highway Planning, Federal Highway Administration.

APPENDIX D

Exposure to $L_{dn} \geq 60$, 70, and 75 dB

The noise exposure calculations presented in the body of this report are primarily for exposure to $L_{dn} \geq 65$ dB. This Appendix contains parallel calculations for exposure above three other levels. The formats for figures in this Appendix are the same as for similar figures in the body. For clarity in using the figures, the annotation has been shortened. Curves may be identified by comparing with the fully annotated figures in the main text. The correspondence between the two are summarized below.

Appendix Figures:	Format Same as Main Text Figure:
D-1, D-6, D-11	9, 10
D-2, D-7, D-12	11
D-3, D-8, D-13	12
D-4, D-9, D-14	13
D-5, D-10, D-15	14

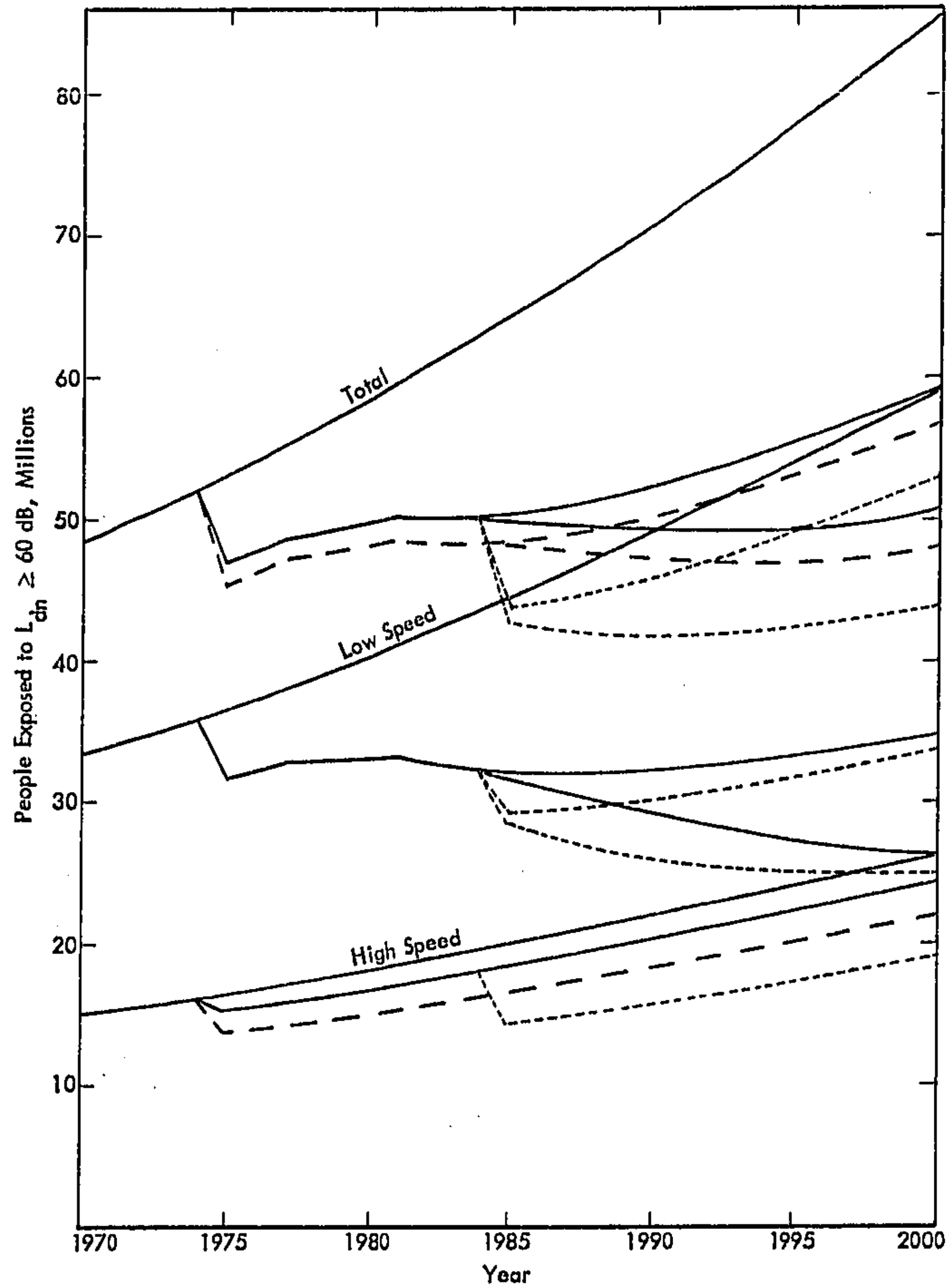

Figure D-1. Exposure to $L_{dn} \geq 60$ dB for Truck Noise Regulations

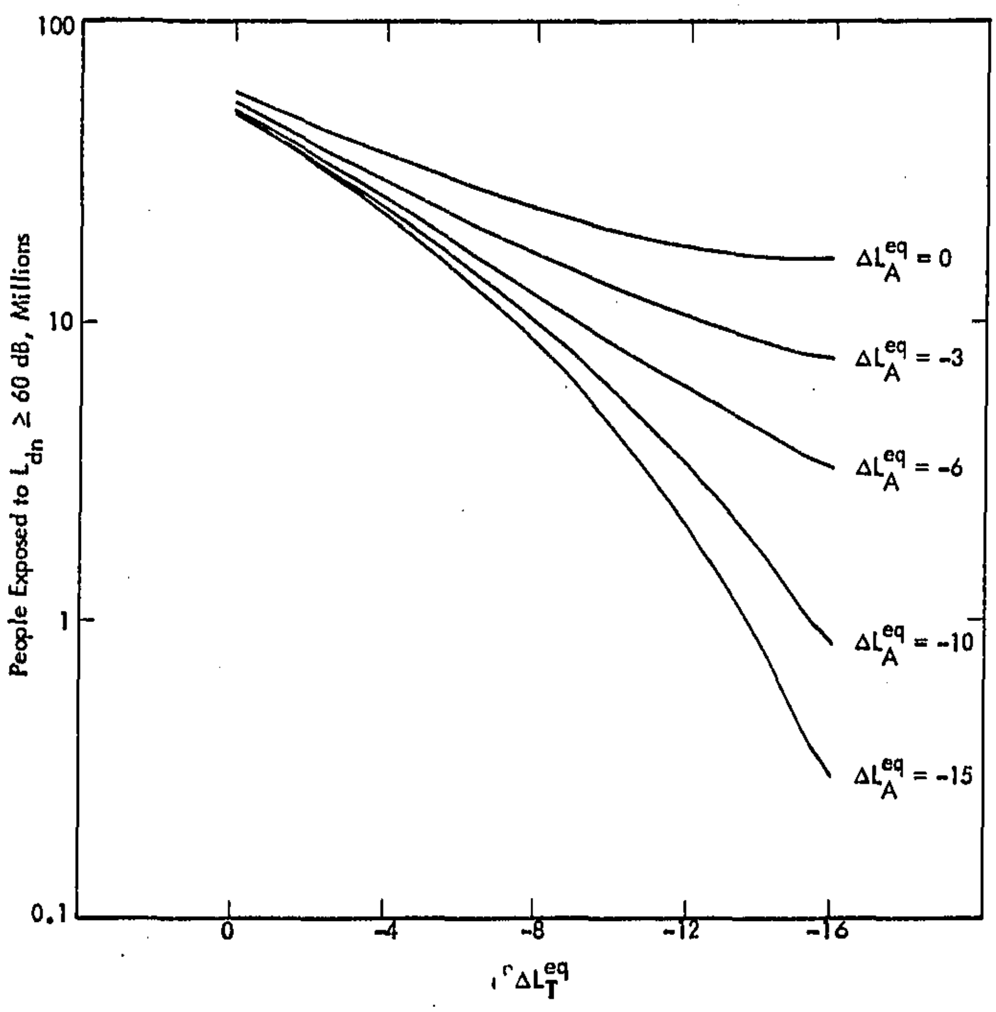

Figure D-2. Exposure to $L_{dn} \geq 60$ dB From Low-Speed Roads in 2000 For Various Reductions to Vehicle Levels

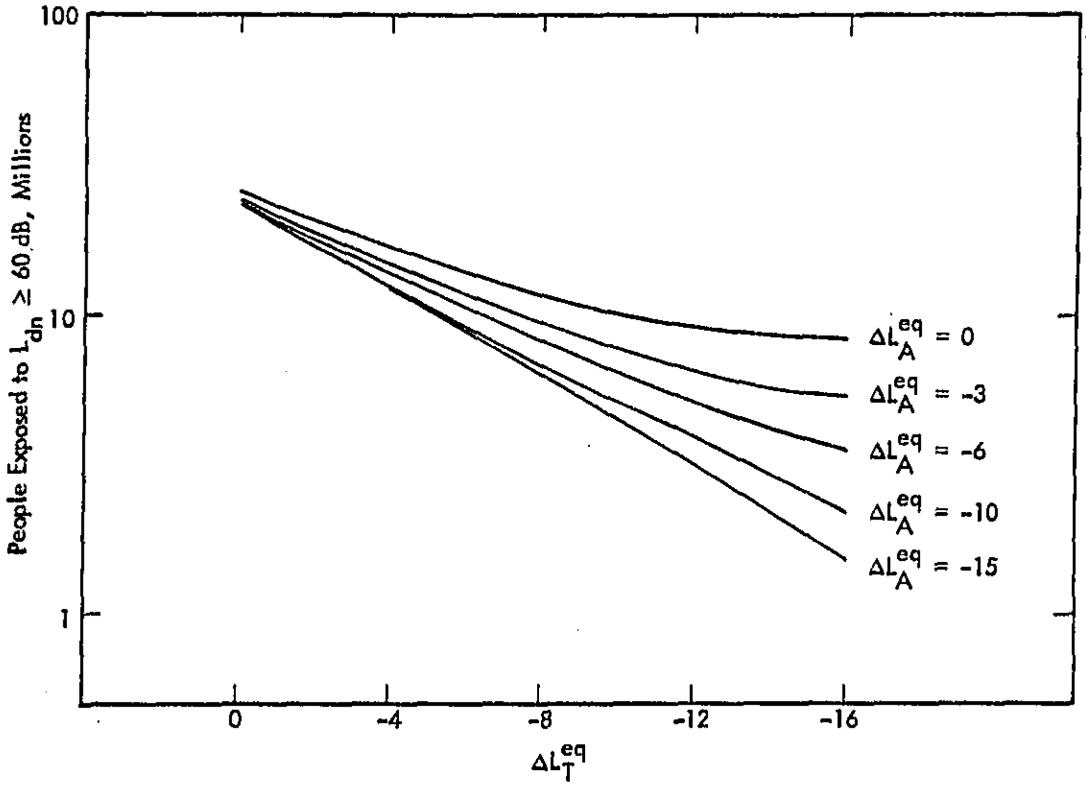

Figure D-3. Exposure to $L_{dn} \geq 60$ dB From High-Speed Roads in 2000 For Various Reductions to Vehicle Levels

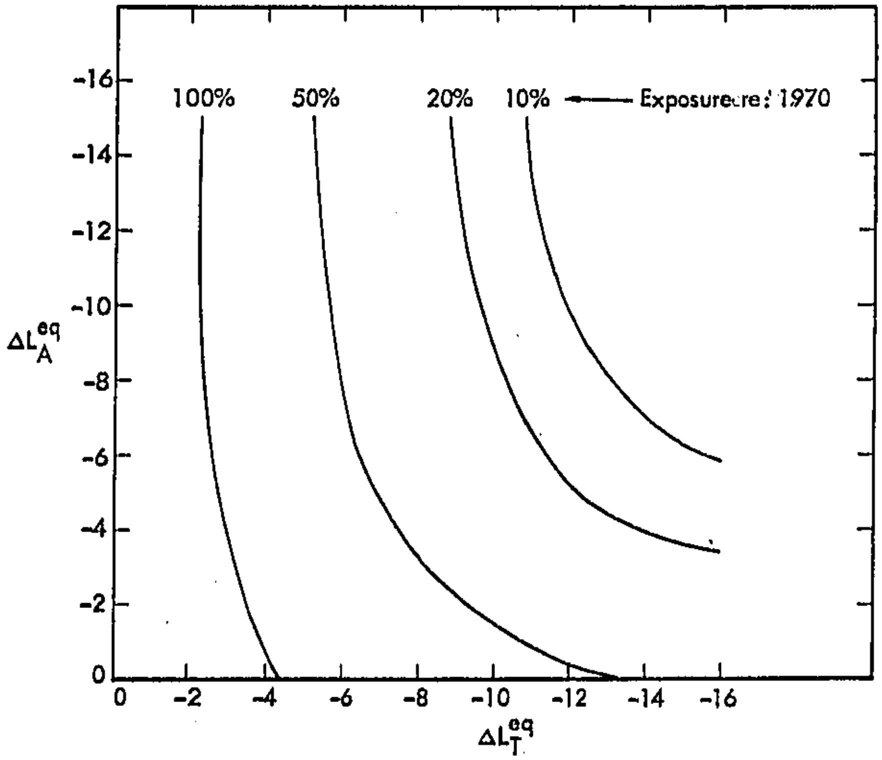

Figure D-4. Vehicle Noise Reductions Required to Reduce Low-Speed Exposure to $L_{dn} \geq 60$ dB in 2000.

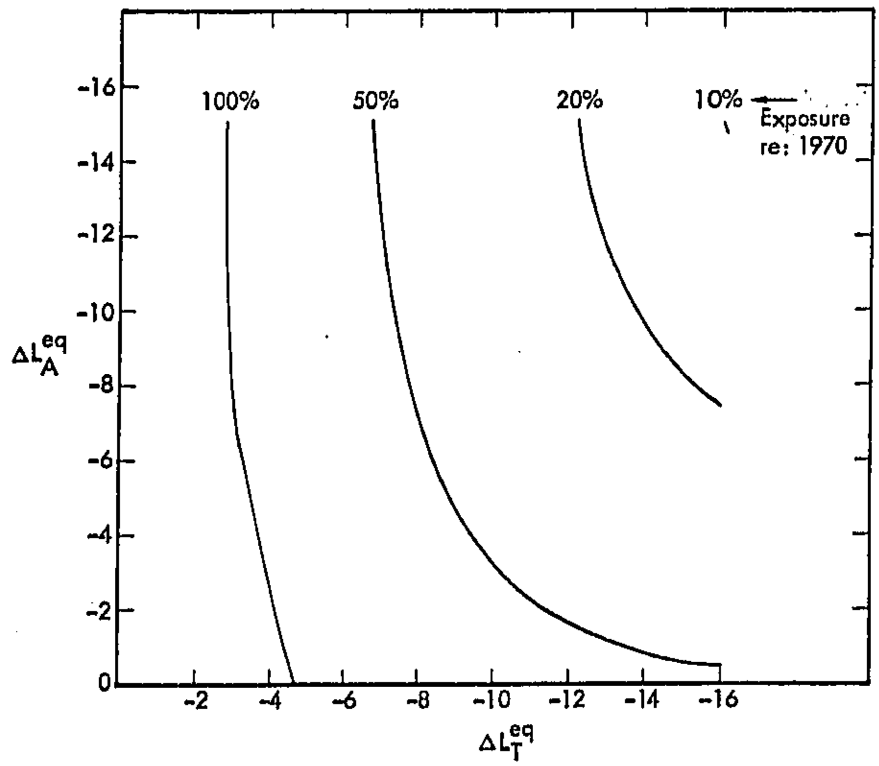

Figure D-5. Vehicle Noise Reductions Required to Reduce High-Speed Exposure to $L_{dn} \geq 60$ dB in 2000.

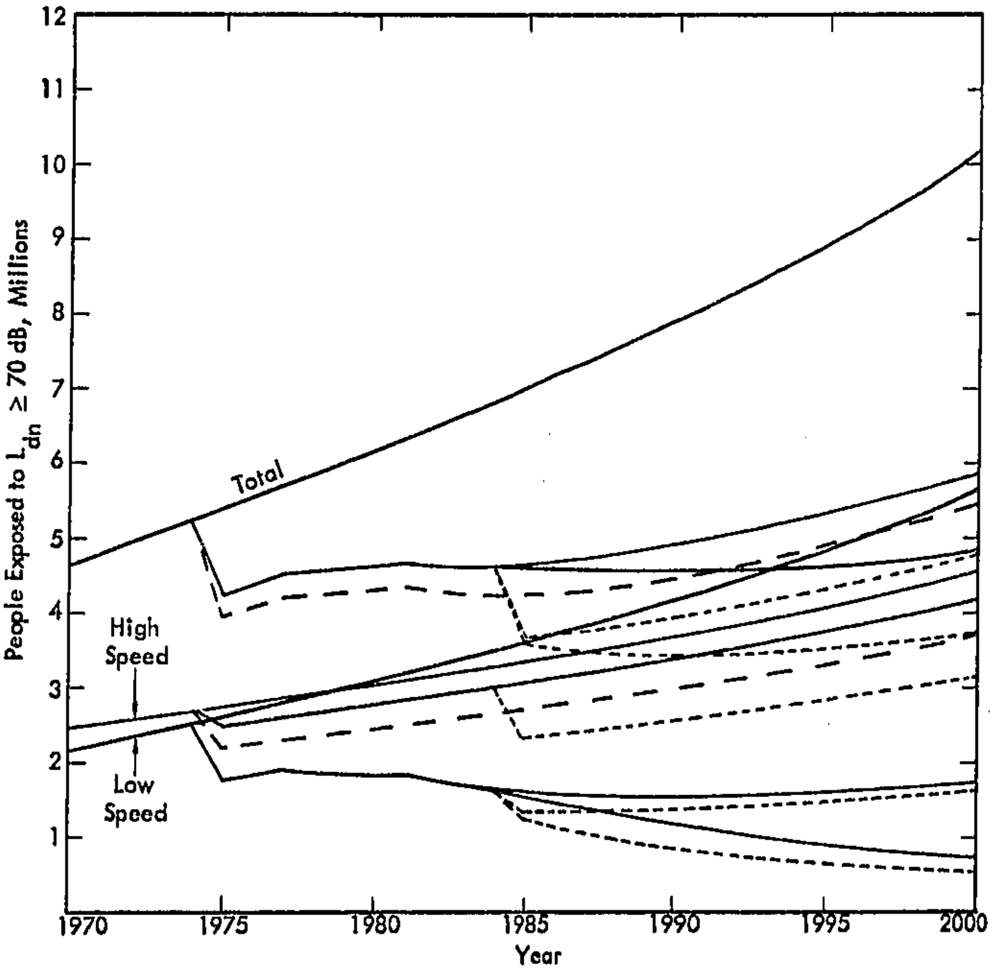

Figure D-6. Effect of Truck Noise Regulations on Exposure to $L_{dn} \geq 70$ dB

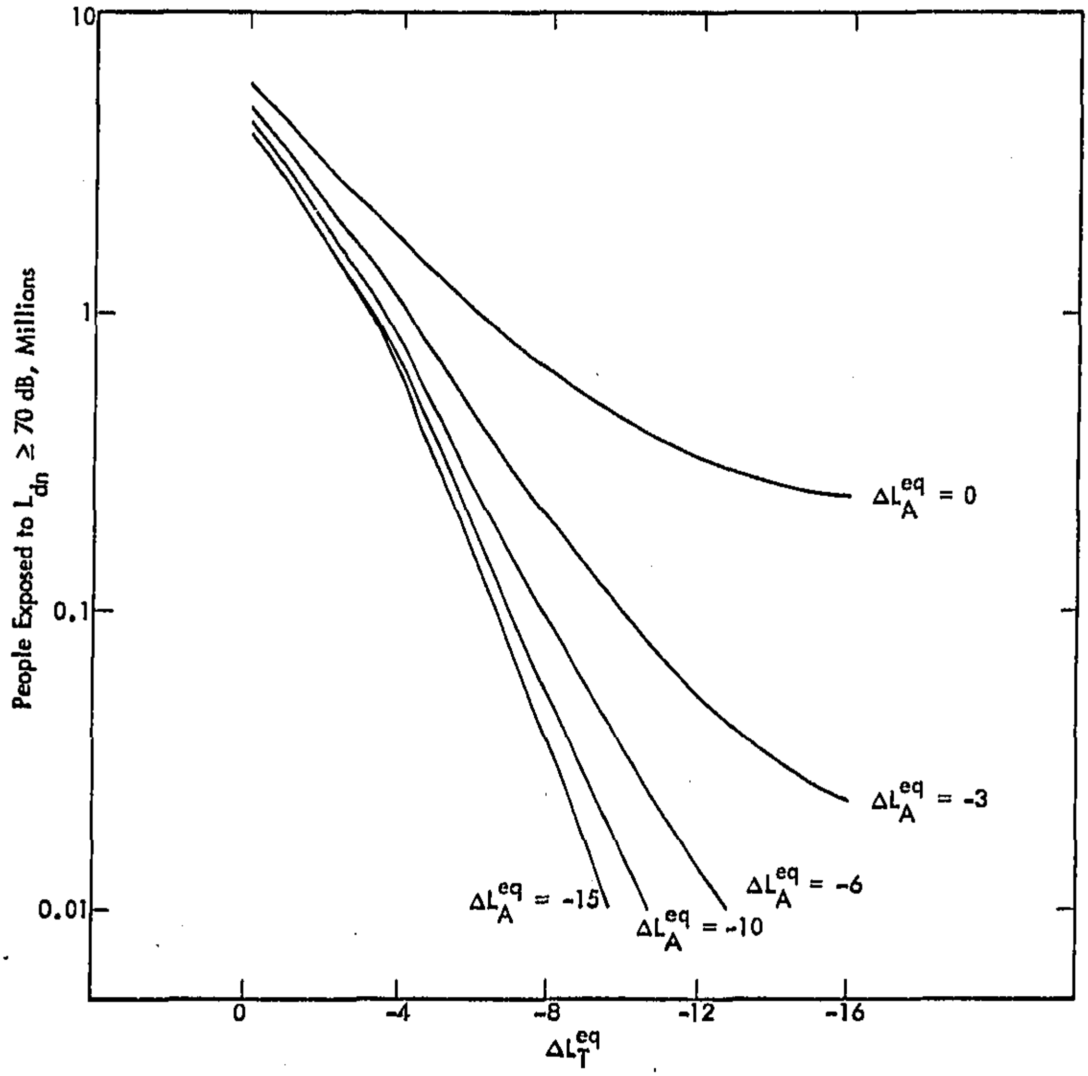

Figure D-7. Exposure to $L_{dn} \geq 70$ dB From Low-Speed Roads in 2000 For Various Reductions to Vehicle Levels

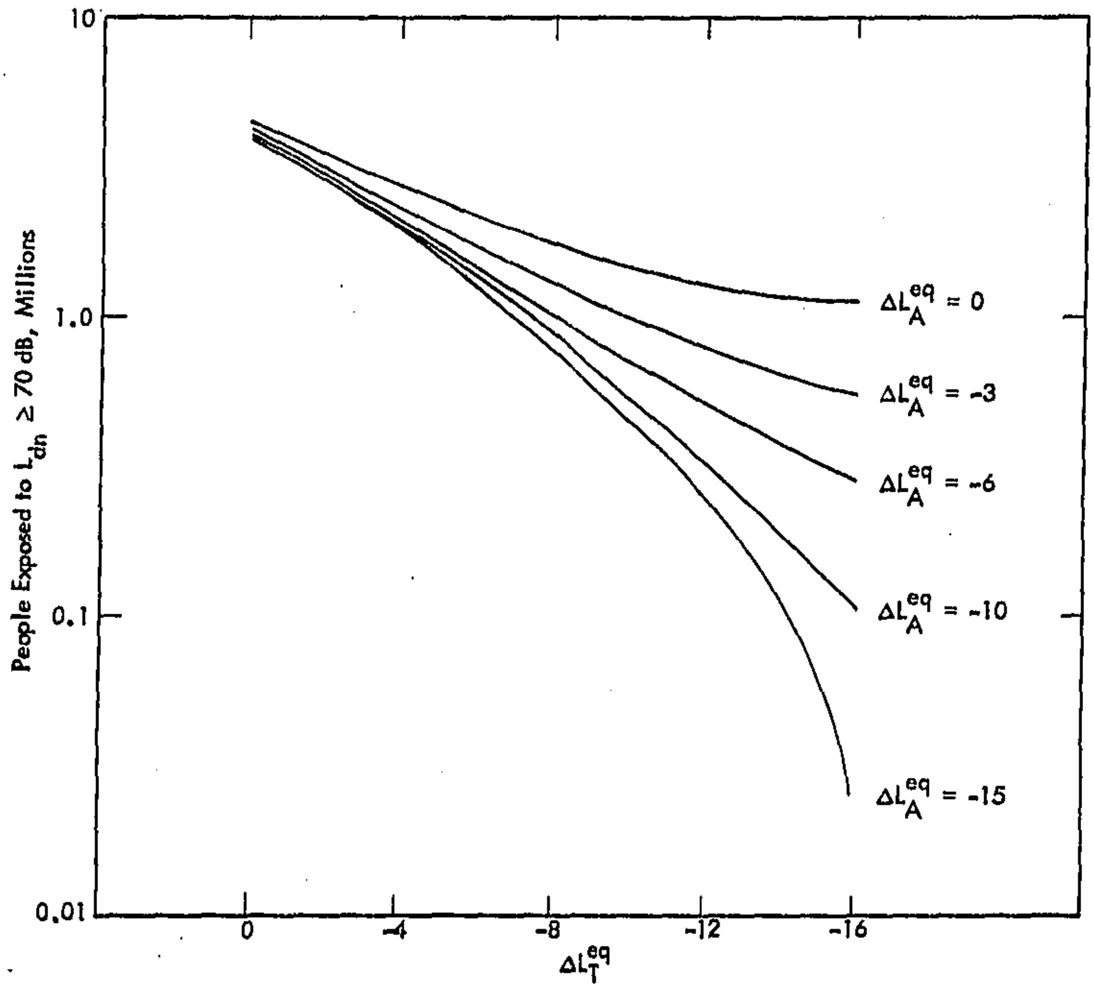

Figure D-8. Exposure to $L_{dn} \geq 70$ dB From High-Speed Roads in 2000 For Various Reductions to Vehicle Levels

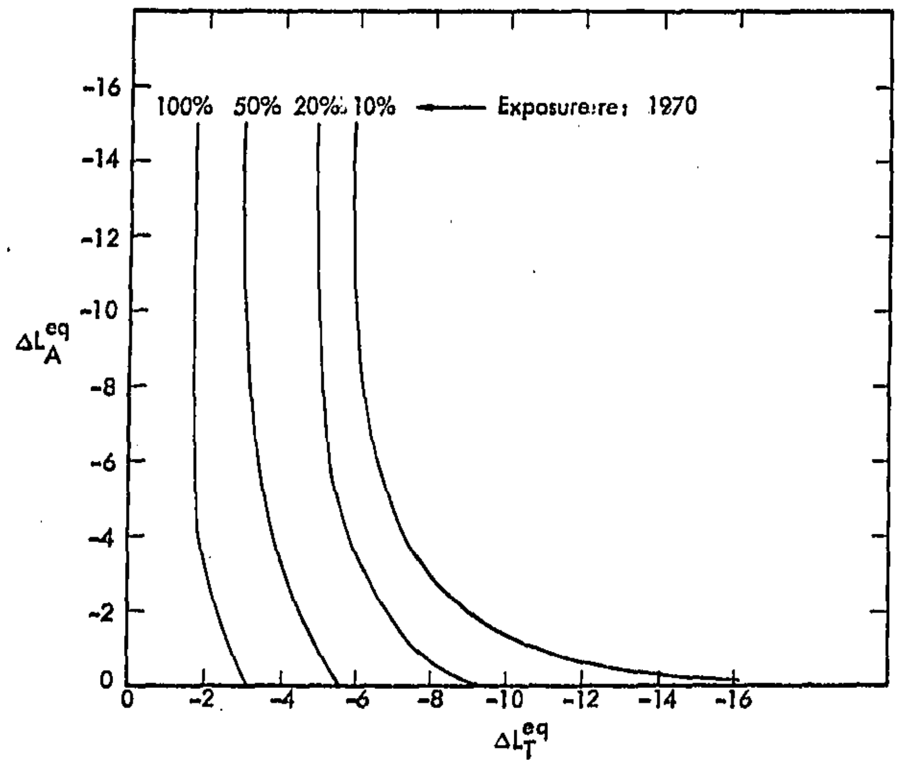

Figure D-9. Vehicle Noise Reductions Required to Reduce Low-Speed Exposure to $L_{dn} \geq 70$ dB in 2000

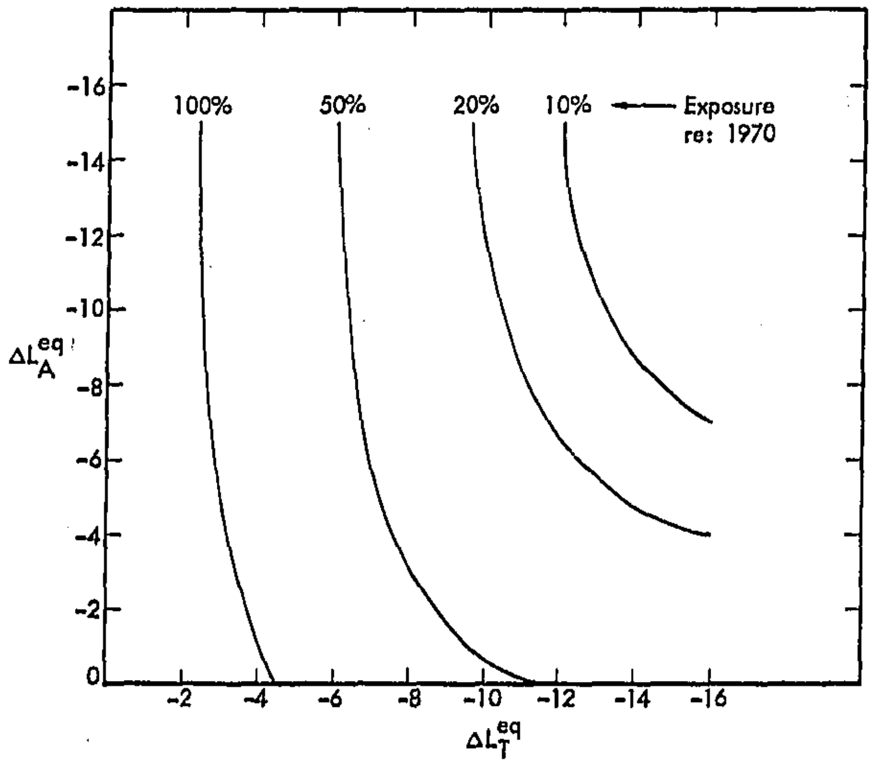

Figure D-10. Vehicle Noise Reductions Required to Reduce High-Speed Exposure to $L_{dn} \geq 70$ dB in 2000.

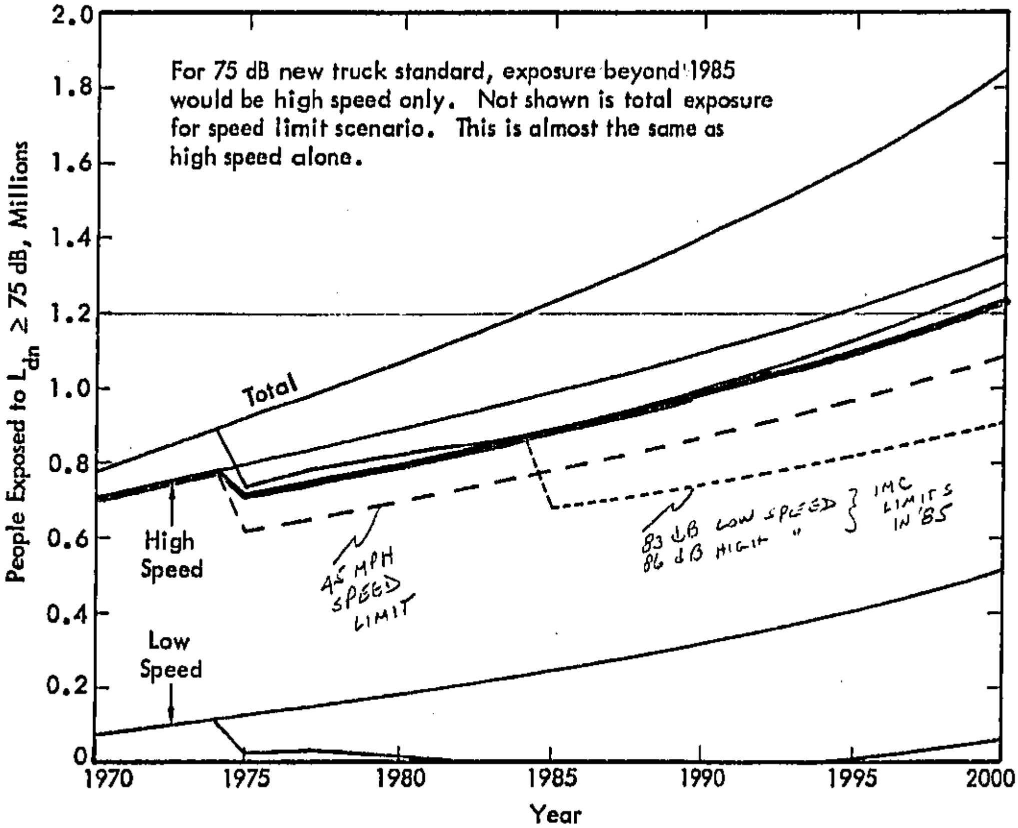

Figure D-11. Effect of Truck Noise Regulations on Exposure to $L_{dn} \geq 75$ dB

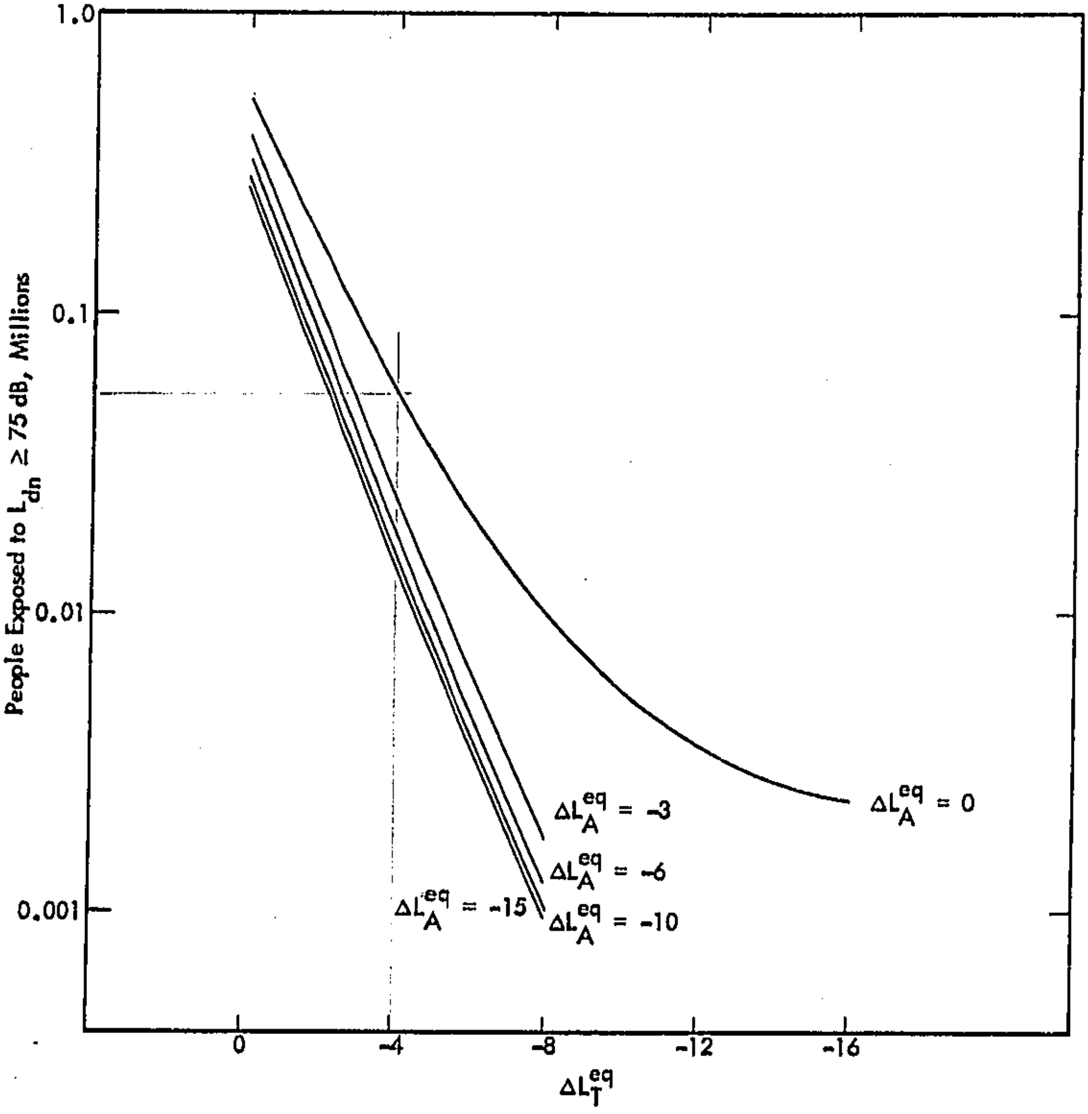

Figure D-12. Exposure to L_{dn} ≥ 75 dB From Low-Speed Roads in 2000 For Various Reductions to Vehicle Levels

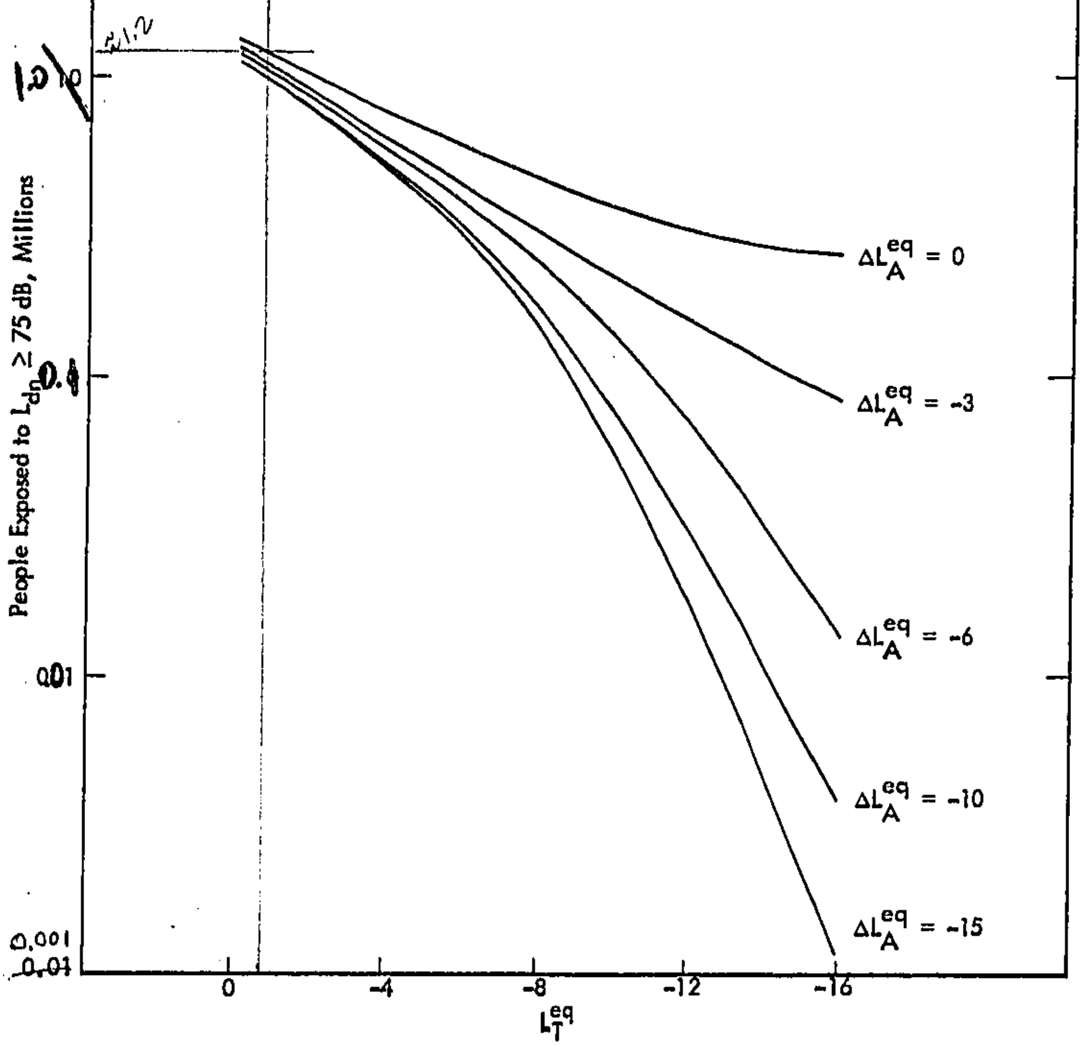

Figure D-13. Exposure to $L_{dn} \geq 75$ dB From High-Speed Roads in 2000
For Various Reductions to Vehicle Levels

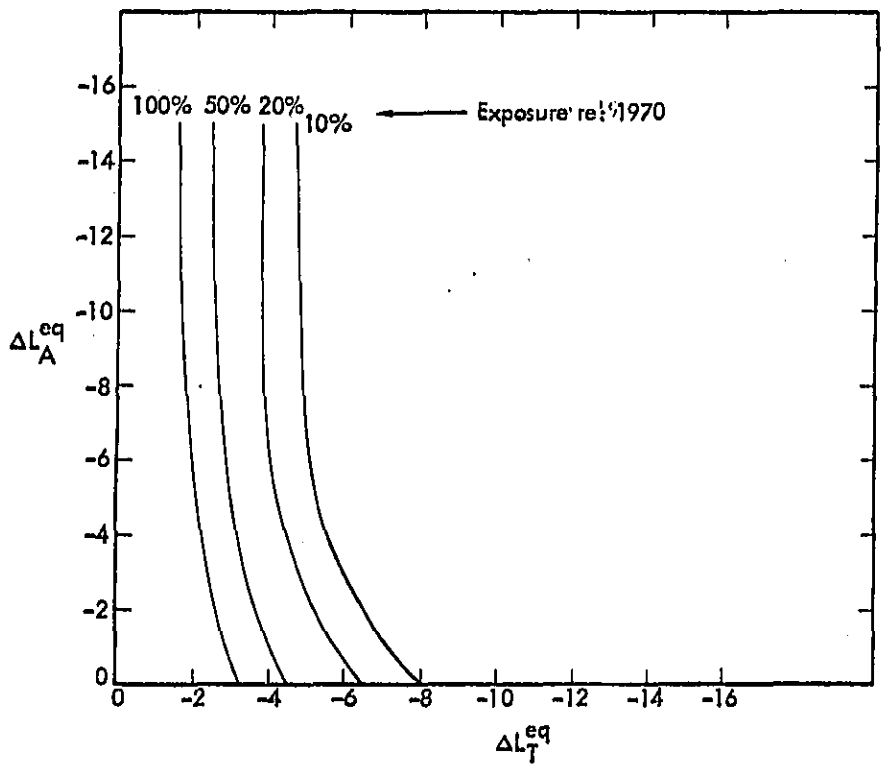

Figure D-14. Vehicle Noise Reductions Required to Reduce Low-Speed Exposure to $L_{dn} \geq 75$ dB in 2000

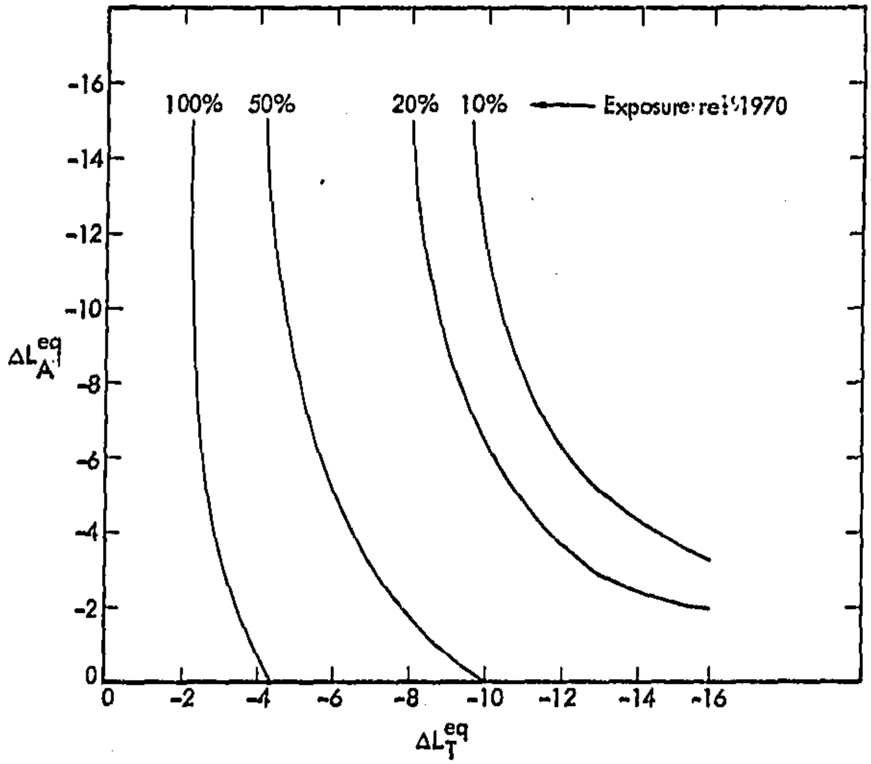

Figure D-15. Vehicle Noise Reductions Required to Reduce High-Speed Exposure to $L_{dn} \geq 75$ dB in 2000