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REGULATION OF INDIRECT SOURCES OF AIR POLLUTION

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The Division of Air Pollution Control, Illinois Environmental Protection Agency, has conducted an ambient air quality monitoring project focusing on carbon monoxide levels in and around several indirect sources. An analysis of the data indicates that highway types of pollutant emissions have the greatest impact on receptors in the vicinity of indirect sources. This implies that the principal, localized constraint on the siting of indirect sources will be the carbon monoxide generated on public roadways servicing those indirect sources. Clearly, adequate procedures must be developed to link such highway types of emissions to pollutant concentrations. Area-source and line-source models were tested by using the data generated during the monitoring project. Favorable results were achieved by using the line-source model. The proper siting of indirect sources involves the allocation of roadway capacity by the governmental units that are responsible for transportation network design and that work in conjunction with regional planning bodies. A regulatory structure is suggested that emphasizes a regional approach, and an example of an air quality allocation scheme is given. The methodology is applicable to all automotive air pollutants although, in general, localized sensitivity is lost for nitrogen dioxide and photochemical oxidants.

•RECENTLY, it has become increasingly evident that the effective solution of environmental problems must go beyond the confines of a single environmental protection agency. The interrelationships among planning, transportation, and environmental activities have become obvious; the mechanisms for translating these interrelationships into meaningful governmental action have not been so obvious. Recently, the attention of air pollution agencies has been focused on the long-range impact on air quality of transportation plans and indirect sources (facilities that, in and of themselves, may not be a source of air pollution but that, because of induced activities such as the attraction of automobiles, may cause air pollution problems). Therefore, transportation agencies have been directed by the Federal Highway Administration to evaluate regional transportation plans for consistency with state implementation plans for air pollution control (1). Likewise, the U.S. Environmental Protection Agency has directed air pollution agencies to develop regulations governing the air pollution aspects of indirect source development (2) and has (a) established requirements for the development of air quality maintenance area (AQMA) plans designed to ensure the long-term maintenance of the national ambient air quality standards in those areas where, primarily because of growth, one or more of the standards might be exceeded during the 1975-85 period (2); (b) promulgated parking management regulations that are to be implemented as part of comprehensive transportation control programs designed to minimize pollutant emissions from vehicles (3); and (c) developed regulations to prevent the significant deterioration of air quality (4).

As part of a program to accomplish these tasks, a regulatory concept designed to provide a framework within which transportation, regional planning, and environmental matters can receive adequate consideration has been developed. The approach is the outgrowth of discussions between the Division of Air Pollution Control; the Bureau of Environmental Sciences, Illinois Department of Transportation; the Northeastern Illinois Planning Commission; the League of Women Voters, and other organizations cognizant of the complexity of the interrelationships among transportation, regional planning, and the environment.

Pursuant to an order of the U.S. Court of Appeals for the District of Columbia Circuit in the case of Natural Resources Defense Council, Inc., et al. versus the U.S. Environmental Protection Agency (5), EPA has established requirements that states must fulfill in regard to air contaminants associated with indirect sources. Highways, shopping centers, stadiums, and residential, commercial, or industrial developments are examples of indirect sources that may induce sufficient pollution-producing activities to threaten the attainment or maintenance of national clean air standards.

Each state is required to design, as an extension of its implementation plan, a regulatory program (2) to

> ... prevent construction, modification, or operation of a facility, building, structure, or installation or combination thereof, which directly or indirectly results or may result in emissions of any air pollutant in any location which will prevent the attainment or maintenance of a national standard.

The logical regulatory scheme for satisfying this requirement is a permit system. Much concern has been devoted to determining who needs and who does not need to apply for such indirect source permits; however, the more important aspect of the problem, namely, determining standards for the issuance of such permits, has received surprisingly little attention. In fact, many developers in Illinois interpreted early federal guidelines to mean that, if one needs to apply for a permit, one will never receive one.

We will focus on setting standards for the issuance of permits for indirect sources; the criterion of requiring a permit review is relatively unimportant from a clean air standpoint as long as the threshold is set sufficiently low. Setting this threshold then becomes a matter of the associated administrative burden and, in a sense, the degree of fine tuning that one can hope to incorporate in the decision-making process. However, the key to success in anticipating and influencing the design and intensity of the development of indirect sources lies in an appropriate definition of the standards and procedures for issuing the permits.

THE HIGHWAY AS THE KEY ELEMENT

The structure of a regulatory approach to handling indirect sources must be developed with an understanding of the nature of the problem associated with such sources. In the evaluation of the localized impact of indirect sources on ambient carbon monoxide levels, two basic problem areas must be considered:

1. The roadway effect, the impact on air quality of induced vehicular activity on existing or proposed roadways within the region of concern including the indirect source itself; and
2. The area-source effect, the impact on air quality immediately downwind of induced vehicular activity within the zone of the indirect source itself.

Interest was initially focused on the area-source effect, with special attention paid to the size of the parking lot, and on pollution levels in adjacent areas. However, air quality data obtained from a complex source-monitoring project conducted at three shopping centers, a stadium, and a drive-in restaurant in Illinois clearly indicated that pollution levels will generally be highest at receptors subject to roadway types of effects rather than at receptors primarily subject to area-source influences.

The monitoring project data fall into two main categories based on the location of the receptors (i.e., the monitoring instruments):

1. Receptors primarily influenced by roadways (both external to and within the indirect source), and

2. Receptors removed from the immediate vicinity of roadways.

Receptors located in parking lots and not located adjacent to roadways may fall into either category, depending on vehicle activity in the immediate vicinity of the receptor. For example, one of the monitored shopping centers has an in-parking-lot circumferential road with a speed limit of 25 mph (40 km/h). A receptor located near this roadway is often subject to the same influence as a receptor located near a major artery. On the other hand, when the wind is blowing from the receptor toward the roadway, data from such a receptor indicate that it is subject to concentrations more indicative of area sources (i.e., general activity in the parking lot). Data collected during the monitoring of the indirect source were reviewed from the standpoint of comparing these measurements at receptors subject to the roadway effect with simultaneous measurements at a receptor that was primarily subject to area-source influences. The data shown in Figure 1 indicate that the roadway effect is clearly dominant and represents the worst case. The numbers in parentheses represent pairs of observations for which a clear contrast existed between highway and area receptors.

ANALYSIS OF ROADWAY IMPACT

Line-source and area-source models were evaluated by using appropriate data obtained during monitoring of the indirect sources. These data included ambient levels of carbon monoxide, wind speed, wind direction, vehicles entering or leaving the facility, number of vehicles passing on adjacent roadways, average speeds and distances traveled by vehicles within the facility, and other related information. Based on wind direction and receptor location, an appropriate mathematical model (i.e., area- or line-source) was applied to each receptor.

Figure 2 shows the result of using a modeling scheme to estimate concentrations at receptors dominated by roadway types of emissions. This scheme consisted of a combination of a graphical solution to the U.S. EPA HIWAY model and the exponential decay function developed by the General Electric Company (6). The graphical solution to the highway model was used to determine concentrations for receptors located within 33 ft (10 m) of the highway. When receptors were located beyond 33 ft (10 m), the concentration at 33 ft (10 m) was obtained by using a graphical solution to the highway model, and the exponential decay function was applied to that concentration for the remaining distance to the receptors.

Based on the difficulties in precisely describing the atmospheric stability, the traffic-generated turbulence, and the limits on the monitoring devices used in the field study and in estimating pollutant source strength, a fair correlation between calculated and observed concentrations was achieved.

The poor results of the application of the area-source model suggested by the U.S. EPA (2) are shown in Figure 3. For a more successful application of such a model to receptors within indirect sources, the entire formulation on which the abbreviated approach was based should be used with an element size appropriate to the scale involved.

PROBLEM OF ALLOCATION

The observation that the governing, i.e., limiting, aspect of the carbon monoxide problem will be the pollution associated with roadway activities has two immediate consequences:

1. Where such roadway activity occurs within the indirect source, the developer has flexibility to improve the management of the traffic flow and thereby avoid the problem; and
2. Generally, the principal constraint on the siting of an indirect source will be the public roadways over which the induced vehicular traffic travels to reach the indirect source.

Figure 1. Concentrations at highway receptors versus concentrations at area receptors.

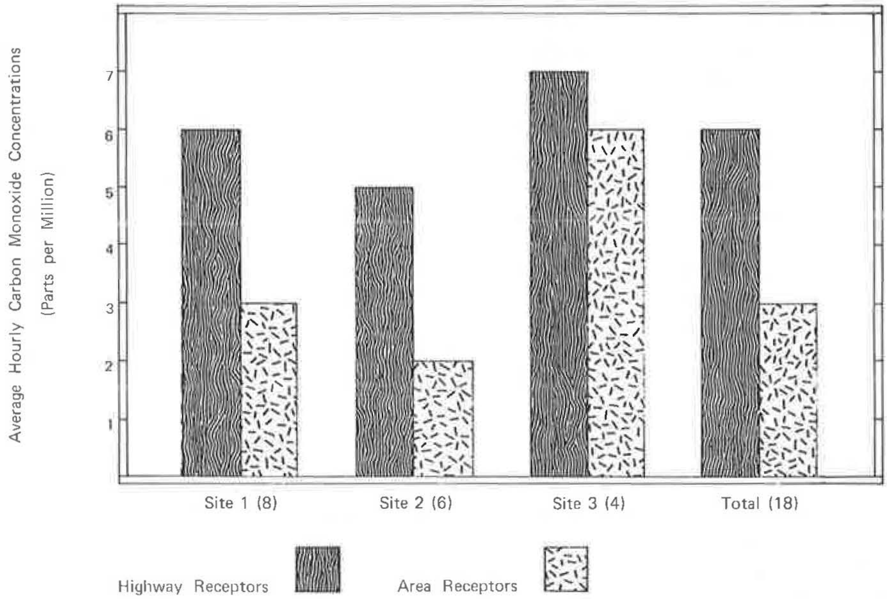
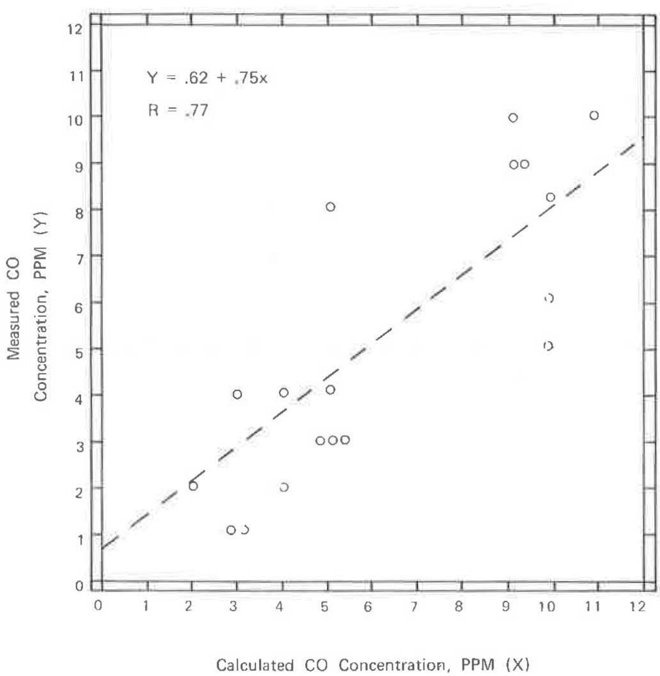


Figure 2. Measured hourly CO concentrations at highway receptors versus concentrations calculated by using modified graphical solution to HIWAY model.



Clearly we must be able to analyze the impact of an individual roadway or network of roadways on air quality if we are to cope with the indirect source problem. Most importantly, it follows from the second consequence that proper handling of the indirect source problem implies controlling the allocation of roadway capacity. This latter conclusion applies, of course, to automotive air pollutants generally, although the effects are often regional in nature (e.g., photochemical oxidants) rather than highly localized. Thus, one is generally concerned with allocation of the network rather than highway-link capacity.

Consider a simple example. A highway is proposed. It must be designed so that at peak activity (which might be the 99th percentile of anticipated demand) clean air standards will not be exceeded. Therefore, associated with the clean air standard is a clean air resource and correspondingly a predetermined, acceptable highway capacity (in terms of vehicles per hour at a reference speed).

The highway when built will immediately have a certain percentage of through traffic satisfying a latent traffic demand. This through traffic consumes a portion of the available clean air resource (i.e., the difference between existing air quality and the applicable air quality standard) that is to be allocated and makes up a portion of the allowable highway capacity corresponding to this available clean air resource.

Evaluating permits so that individual indirect sources can be located along the highway then becomes a process of relating the vehicular traffic induced by the indirect source to the available clean air resource, i.e., the residual highway capacity. Therefore, because the clean air resource is linked directly to highway capacity, we are, in a sense, allocating that capacity as we administer the permit system for indirect sources.

It also follows from this observation that a system that is to effectively handle the indirect source problem must be developed so that it is in accord with whatever governmental system controls the development of a regional transportation network. Although there might be many strategies for controlling growth in a region (e.g., land use planning, energy constraints, and public transit), ultimately they must be viewed in terms of their effect on vehicular traffic so that their principal impact on air pollution levels can be assessed.

STANDARDS FOR ISSUANCE

As mentioned earlier, the most critical aspects of any set of indirect source regulations are the standards and procedures for issuance of associated permits. Such standards, as recommended below, must reflect the nature of the problem (e.g., the roadway dominance), the clean air goals, and the administrative structure by which the regulations will be enforced.

> An indirect source permit shall be granted if and only if the control agency concludes the following:
>
> 1. Public road or highway as indirect source—Construction or modification of a public road or highway will not result in an increase in the ambient air quality levels of any specified air contaminant by more than 80 percent of the difference between ambient air quality standards and the existing ambient air quality levels of any specified air contaminant and will not result in a violation of ambient air quality standards;
> 2. Other than public road or highway as indirect source—Construction or modification of the indirect source, other than a public road or highway, will not result in an increase in the ambient air quality levels of any specified air contaminant by more than 30 percent of the difference between ambient air quality standards and the existing ambient air quality levels of any specified air contaminant and will not result in a violation of ambient air quality standards; or
> 3. Any indirect source—The indirect source has been recommended for permit by an approved regional planning body as conforming with a regional plan approved by the control agency.

The structure inherent in these recommended standards recognizes a shift in the principal responsibility for permit analysis from ad hoc reviews initiated by the control agency to an integration of air pollution criteria as constraints in the regional planning process. The shift also accommodates a broadening of the regulatory perspective from highly localized carbon monoxide problems to regional impacts of pollutants, such as oxidants of nitrogen, hydrocarbons, and photochemicals.

Items 1 and 2 will be examined in greater detail later; however, suffice it to say at this point that they represent a fairly simple scheme for allocating the available clean air resource and the related highway capacity. This allocation scheme is consistent with the concept of emission density zoning (7). The general approach is similar to the proposed nondegradation policy of EPA relating to suspended particulates and sulfur dioxide (4).

Before item 2 becomes operational in any urban area, several steps should take place:

1. A regional planning agency with adequate geographical scope and technical competence should be approved by the control agency for an active role in issuing permits for the indirect source,
2. The regional planning body should have a comprehensive regional plan in sufficient detail to permit the regionwide estimation of pollutant emissions from highways and associated land use activities for the next 10 years, and
3. The comprehensive plan should be analyzed by the control agency and found adequate for the maintenance of national clean air standards.

The approved comprehensive regional plan then becomes a guide against which proposed indirect sources can be measured for conformity and thereby acceptability in relation to clean air standards. A developer with a nonconforming use could apply directly to the control agency under items 1 and 2 but would have to accept the burden of showing that the nonconforming use would not distort the comprehensive plan and lead to a likely violation of ambient air quality standards during the next 10 years. It is felt that this burden, the potentially greater leniency of item 3, and the compatibility of the development of the highway network with the comprehensive regional plan will offer strong incentives for conforming developments and thereby greatly strengthen the ability of regional planning agencies to implement their comprehensive plans. This latter aspect may be the most far-reaching consequence of the nationwide effort to cope with the attainment and long-range maintenance of ambient air quality standards.

Structurally, this regulatory approach is applicable to all automotive air pollutants. Where stationary sources produce significant additional emissions (e.g., NO_x, particulate aerosols), the focus on the highway network must be broadened to consider emissions associated with alternative land use patterns. Unfortunately, attempts to date to correlate air pollution emissions with industrial land use and zoning classifications have been unsuccessful (8). Reliance on regulatory approaches, such as emission density zoning (7, 9), may therefore be necessary to establish an envelope of maximum air quality degradation associated with a given plan for regional development.

EXAMPLE OF ALLOCATION SCHEME IMPLICIT IN ITEMS 1 AND 2

Associated with any existing or proposed highway is a design capacity that can be defined in terms of the maximum number of vehicles per hour that the highway will accommodate at a specified speed. For reasons of cost effectiveness, the design vehicle activity is usually not the absolute maximum hourly activity anticipated on the highway (e.g., the highest hourly traffic volume that might be expected on July 4); instead, it is some lesser figure, such as the 30th highest hour. Whenever the design capacity of the highway, in terms of vehicles per hour, is exceeded, there is generally a substantial decrease in average vehicle speed leading to an ultimate breakdown in traffic flow. This is particularly important from the standpoint of ambient air quality levels attributable to the roadway effect; as traffic volume increases and average vehicular speed drops, hydrocarbon and carbon monoxide emissions increase. This relationship can

Figure 3. Measured hourly CO concentrations at area receptors versus concentrations calculated by using area-source model suggested by EPA.

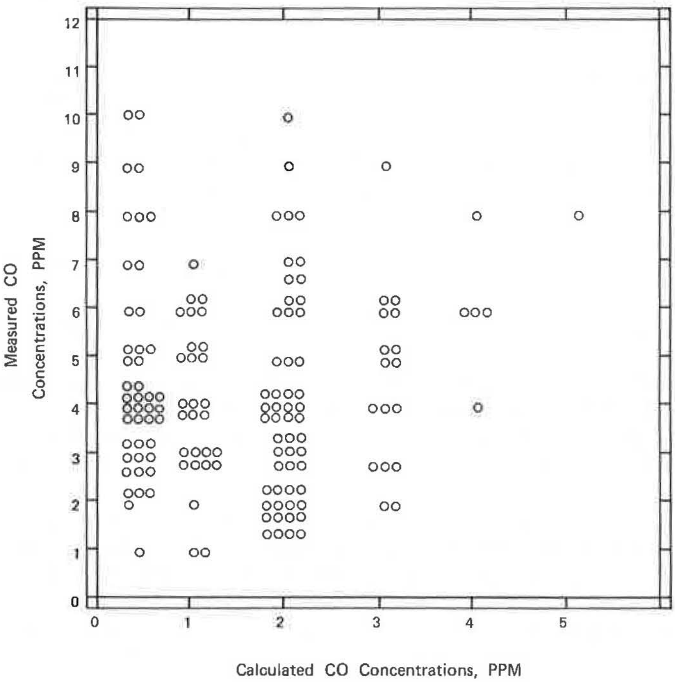
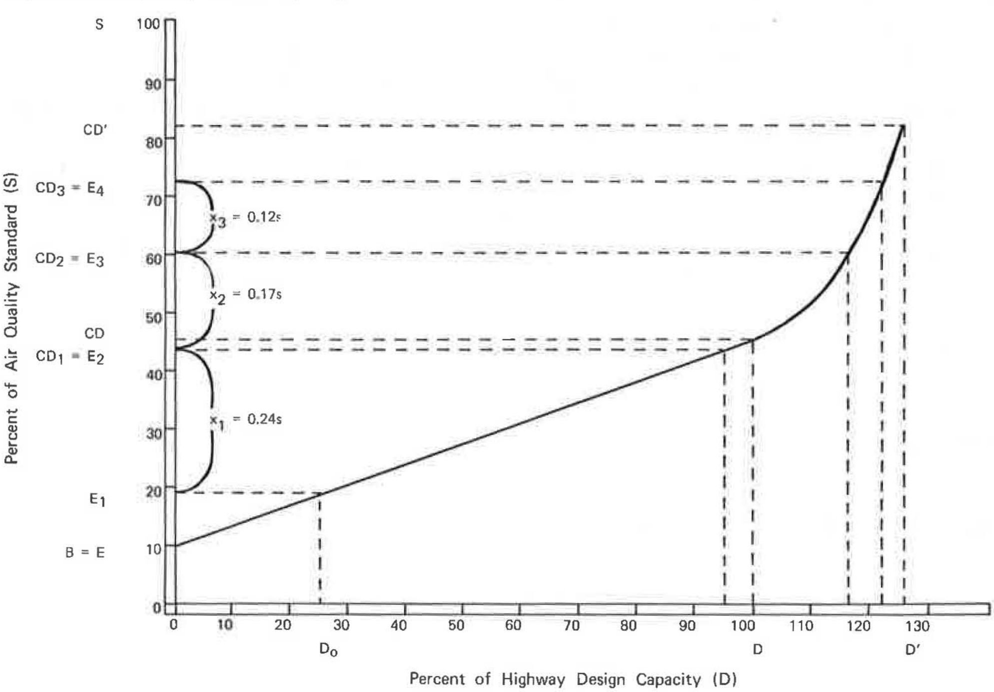


Figure 4. Air quality versus highway traffic.



be illustrated graphically by a curve of air quality versus traffic (Figure 4).

If one assumes some highway design capacity D (i.e., some number of vehicles per hour at a specified average speed), it can be seen that emissions increase linearly with traffic volume as long as the number of vehicles per hour associated with D is not exceeded (obviously this also assumes that these vehicles travel at the design speed). When the design capacity in vehicles per hour is exceeded, however, the curve slopes steeply upward since additional vehicles not only add their own pollution but also slow down existing traffic and thereby greatly increase pollutant emissions.

Consider a hypothetical example for purposes of discussing allocation of the available clean air resource in a particular area and the highway capacity. The notation used in Figure 4 and in our calculations is as follows:

- S = applicable national ambient air quality standard expressed as 100 percent.
- B = background pollutant concentration attributable to sources other than those associated with the proposed highway and associated indirect sources, 10 percent of S for this example.
- E = existing air quality, background concentration plus concentrations attributable to the busiest highway affected by the proposed indirect sources.
- D = design capacity of a proposed highway, representing the maximum number of vehicles per hour for which an assumed design speed of 50 mph (80 km/h) can be maintained.
- D′ = design figure for air quality purposes, the maximum number of vehicles per hour for which an indirect source permit can be issued, which equals the number of vehicles per hour at a specified speed equivalent to an air quality level (for highways) of 0.8 (S - E) in accordance with items 1 and 2. For this example, assume a number of vehicles per hour equivalent to the 99th percentile of maximum anticipated traffic and a likely speed at D′ of 15 mph (24 km/h).
- CD′ = ambient pollutant concentration at D′ = E + 0.8 (S - E).
- CD = ambient pollutant concentration at D.
- X_R = contribution that the proposed public roadway may make to ambient pollution levels, expressed as a percentage of S; S_R = 0.8 (S - E).
- X = contribution that an indirect source, other than a public roadway, may make to ambient pollution levels, expressed as a percentage of S; X = 0.3 (S - E).
- F = speed (1 mile = 1.6 km) correction factor, emissions at 50 mph/emissions at 15 mph = 0.6, for this example.
- V = traffic volume correction factor = vehicles per hour at D/vehicles per hour at D′.

We based the following calculations for a proposed highway subject to the requirements in item 1 on the definitions given above.

$$X_R = 0.8\,(S - E)$$

If we assume that E = B, then

$$X_R = 0.8\,(S - B) = 0.8\,(S - 0.1S) = 0.72S$$

and the ambient pollutant concentration at D′, the design figure for air quality purposes, is

$$CD' = E + 0.8\,(S - E) = B \pm 0.8\,(S - B) = B \pm X_R = 0.1S + 0.72S = 0.82S$$

For illustrative purposes, further assume that the traffic volume at D′ is 125 percent of the traffic volume at D; then, the ambient pollutant concentration at D can be determined by proportion as follows:

$$CD = (CD' - E)(V)(F) + E = (0.82S - 0.1S)(100/125)(0.6) + 0.1S = 0.45S$$

Now consider the situation where there is a desire to successively build several indirect sources along a segment of this newly constructed highway. Assume a steady through-traffic volume D_o (independent of local indirect sources) of 25 percent of the traffic volume associated with the highway design capacity D. This assumption establishes a new existing air quality level E_1, where

$$E_1 = 0.25\,(CD - E) + E = 0.25\,(CD - B) + B = 0.25\,(0.45S - 0.1S) + 0.1S = 0.19S$$

Considering a proposed indirect source 1 and applying the 30 percent criterion in item 2 give the allowable contribution or addition to pollution levels as

$$X_1 = 0.3\,(S - E_1) = 0.3\,(S - 0.19S) = 0.24S$$

and the resultant ambient pollutant concentration is projected to be

$$CD_1 = X_1 + E_1 = 0.24S + 0.19S = 0.43S$$

In this example, Figure 4 shows that indirect source 1 has brought the traffic level (i.e., $CD_1 = 0.43S$) on the highway segment nearly to the highway capacity design level D (i.e., $CD = 0.45S$). Thus, it appears that either the road segment was designed specifically for this first indirect source or it was grossly underdesigned.

At this point, it should be noted that in practice most indirect sources will not use the full 30 percent allowed by item 2 [i.e., 0.3 (S - E)] if the road segment is adequately designed. As an illustration of the size of a facility that uses the full 30 percent, consider a large suburban shopping center [approximately 1.25 million ft^2 (0.12 million m^2) of floor area] observed during the monitoring of the indirect source conducted by the Division of Air Pollution Control. It is estimated that this facility attracts approximately 4,000 vehicles per hour during its busiest 8 hours, and this traffic flows primarily on two four-lane roads adjacent to the facility (i.e., about 2,000 vehicles per hour per road). When the modified version of the U.S. EPA HIWAY model was used, the 8-hour national ambient air quality standard for carbon monoxide can be expressed in terms of 7,000 vehicles per hour at an average speed of a little over 25 mph (40 km/h). Before this shopping center was built, the existing air quality during the 8-hour period of maximum traffic on the busiest roadway is estimated to have been equivalent to about 500 vehicles per hour. This traffic flow occurred on one of the four-lane roadways adjacent to the facility. Based on the preceding information, application of the 30 percent rule (item 2) would not have prevented the construction of this large shopping center [i.e., $0.3 \times (7{,}000 - 500) \cong 2{,}000$].

The next proposed indirect source to be constructed along the example roadway segment, indirect source 2, must be evaluated in terms of a new existing air quality level E_2, where

$$E_2 = CD_1 = 0.43S$$

Thus, the allowable contribution of indirect source 2 to pollution levels is

$$X_2 = 0.3\,(S - E_2) = 0.3\,(S - 0.43S) = 0.17S$$

and the resultant ambient pollutant concentration is projected to be

$$CD_2 = X_2 + E_2 = 0.17S + 0.43S = 0.60S$$

This situation can be characterized by a rush-hour period during which one might expect peak through traffic on the roadway to overlap peak activity periods at indirect sources 1 and 2. Figure 4 shows that, in our example, an ambient concentration of 0.60S is associated with roadway traffic at about 116 percent of design capacity D, and, correspondingly, a lower average speed, assumed to be 30 mph (48 km/h). It also shows that of this 116 percent, the through traffic D_o accounts for 0.25D, indirect source 1 for 0.70D, and indirect source 2 for 0.21D. In reality, this traffic-load distribution could change if indirect source 2 could adjust its operations so that its peak traffic demand did not coincide with peak roadway traffic or that due to indirect source 1. This would permit a greater amount of vehicular activity at indirect source 2. Additionally, this type of operational adjustment is particularly important as it relates to subsequent development along the affected road segment.

For indirect source 3, the new existing air quality level E_3 is

$$E_3 = CD_2 = 0.60S$$

and the allowable contribution of indirect source 3 to pollution levels is

$$X_3 = 0.3\,(S - E_3) = 0.3\,(S - 0.60S) = 0.12S$$

The resultant ambient pollutant concentration is projected to be

$$CD_3 = X_3 + E_3 = 0.12S + 0.60S = 0.72S$$

From Figure 4, CD_3 is associated with a traffic level of 122 percent of the highway design capacity D; only 6 percent of this load is due to indirect source 3. Obviously, the same types of operational adjustments that were open to indirect source 2 are possibly available to source 3; the potential for increased vehicular activity exists.

There is a point beyond which no more indirect sources that require permits can be permitted. For example, regulations proposed in Illinois require permits only from indirect sources likely to cause increases in carbon monoxide in excess of 10 percent of the national standard S. Thus, since indirect source 4 would only be allowed to contribute 8 percent of the standard $[X_4 = 0.3\,(S - CD_3) = 0.3\,(S - 0.72S)]$ to pollution levels, if it applied for a permit (i.e., if its likely contribution was greater than or equal to 10 percent of the standard), it probably would not receive one. This conclusion does not imply that no more indirect sources would be built, however. Many less polluting activities (outside the permit system) could prevail, and off-peak hours could accommodate new, large sources if appropriate operational adjustments were made as previously noted.

However, in essence, we have, for the time being, called a halt to that aspect of regional expansion relying on the highway segment in question. We see therefore an inherent braking mechanism in the proposed regulatory measure that will suffice until a more comprehensive approach based on regional planning concepts can be implemented under item 3 of the recommended standard for issuance.

Note that Figure 4 and associated calculations assume a single functional relationship between vehicular emissions and traffic conditions. In actuality this relationship will strongly depend on the temporal impact of the Federal Motor Vehicle Control Program. The calculations would proceed essentially as outlined except one would use vehicular emission factors appropriate to the likely age distribution of vehicles during the future year under investigation.

RELATIONSHIP OF INDIRECT SOURCE REGULATION TO OTHER PLANNING ACTIVITIES

It is important to recognize that any indirect source regulation is only one of the tools that should be used in the implementation of a comprehensive planning process designed to provide for the rational use of available clean air resources. From an air pollution standpoint, the framework for this comprehensive planning process presently consists of the U.S. EPA planning activity for AQMAs, the proposed federal policy regarding the prevention of significant air quality deterioration, and the FHWA requirement for the environmental review of transportation plans for standard metropolitan statistical areas to ensure that they are consistent with state implementation plans for air pollution control.

The general concept of AQMA planning, if applied to all geographical areas, is broad enough to encompass each of these program elements; however, there are significant institutional and administrative barriers to the successful application of such a concept. Working relationships among environmental agencies, regional planning commissions, and local municipal bodies must be established or clarified; both public and private interest groups must have the opportunity for meaningful input into planning activities; and the environmentally related efforts of all other concerned agencies must be integrated with the entire process. Most assuredly, the question is not whether the necessary decisions will be made but how they will be made. Thus, it is vital that planning factors such as indirect sources regulations be consistent with the overall plan. The approach suggested in this paper is designed to accomplish that end.

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COMPARISON OF AUTOMOBILE EMISSIONS BASED ON TRIP TYPE IN TWO METROPOLITAN AREAS

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Estimates of the distribution of automobile emissions among various trip types in the Washington, D.C., area are developed and compared with analogous estimates previously reported for Allegheny County, Pennsylvania. Work trips produce approximately equal proportions of emissions in both regions. However, trips to and from the central area and short trips are of considerably lesser importance in Washington than in Allegheny County. In addition, cold starts and evaporations produce a smaller proportion of emissions in the Washington area than in Allegheny County. These results suggest several ways in which measures that are effective in reducing automobile emissions in Washington are likely to differ from measures that are effective in achieving the same objective in Allegheny County. For example, improved suburban transit service and disincentives to suburban automobile travel are likely to be of greater importance in the Washington area than in Allegheny County. Jitney service or other measures oriented toward short trips may be of greater value in Allegheny County. In both regions, however, control of emissions from trips with one or both ends in the suburbs is necessary to achieve substantial reductions in regional automobile emissions.

•REDUCTION of automobile emissions of carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_x) is a major objective of programs to improve air quality in urban areas. One of the many possible approaches to achieving this objective is to reduce automobile travel. Measures through which this might be accomplished include car pooling, transit improvements, and fees for or restrictions on automobile use.

Many measures to reduce automobile use can be expected to most significantly affect certain clearly identifiable portions of urban area automobile travel and to have little or no effect on other portions of automobile travel. For example, increased use of freeway bus systems and bus priority are most likely to affect long trips; however demand-responsive transit might be best suited to short trips. Park-and-ride transit service may reduce automobile vehicle miles (kilometers) traveled (VMT) but is unlikely to reduce automobile trip frequencies. Transit improvements generally may be best suited to work trips or trips to and within high-density areas, but other types of trips may be responsive to certain kinds of automobile fees or restraints. Because measures to reduce automobile use do not affect all types of trips equally, the potential effectiveness of emissions reduction of such measures depends on the distribution of automobile emissions among trips of various purposes, lengths, origins, and destinations.

The distribution of emissions among trip types and the potential effectiveness of measures to reduce automobile use and emissions can be expected to vary from city to city, depending on such factors as the lengths and geographical distribution of trips. Estimates of the automobile emissions attributable to various types of trips in Allegheny County, Pennsylvania, were presented in a previous paper (1). In this paper, the analysis is extended to the Washington, D.C., area. Estimates are presented of diurnal evaporative HC emissions, which are independent of travel behavior; cold-start and hot-soak emissions, which depend on trip volume but not on trip length; and the distributions of emissions according to trip purpose, length, origin and destination, and time of day. The Washington results are compared with those previously obtained for Allegheny County, and implications for the potential emissions-reduction effectiveness of measures to reduce automobile use in the two regions are discussed.

METHODOLOGY

The Washington emission estimates were developed for an 870-mile^2 (2250-km^2) area surrounding Washington, D.C. (Figure 1). Data from the 1968 Washington transportation survey were obtained from weekday automobile driver trips between traffic zones in the Washington area for home-based (HB) work, shopping, school, social-recreational, and all other trips during peak and off-peak periods. Peak-period trips were defined as trips terminating in the periods from 7:10 to 9:10 a.m. and from 4:40 to 6:40 p.m. Roadway distances between each zone pair and zone-to-zone travel times were also obtained. Average zone-to-zone speeds were computed by dividing trip lengths by travel times.

The data were used to develop projections of automobile emissions attributable to Washington area internal trips in 1975 subject to the assumption that travel patterns in 1975 will be the same as those in 1968. This approach, which was also used in the Allegheny County study, enables the emission estimates to reflect the effects of automobile emission controls and avoids the need to develop projections of growth. The emission estimates presented therefore apply to a hypothetical region whose 1975 travel patterns are the same as the Washington area internal trip patterns of 1968.

Emissions were computed for each trip in the Washington area data set and then were summed over trip types to obtain emission estimates by trip type. Since the age of the vehicle used for a given trip is not included in the data, emissions for each trip were averaged over the age distribution of the Washington area automobile population. The emission estimation model that was used is described in detail elsewhere (1) and is presented in abbreviated form as follows:

$$E_p = L\,[s_p(v)\,e_p + k_p] + \alpha c_p + h_p \tag{1}$$

where

- E_p = emissions of pollutant p attributable to a trip in kilograms,
- L = length of trip in miles (kilometers),
- $s_p(v)$ = speed adjustment factor for pollutant p and trip speed v,
- e_p = running exhaust emissions of pollutant p in kilograms per mile (kilometer) averaged over the vehicle population,
- k_p = crankcase emissions of pollutant p in kilograms per mile (kilometer) averaged over the vehicle population (nonzero only for HC),
- α = 1 if trip begins with a cold start and zero otherwise,
- c_p = cold-start emissions of pollutant p in kilograms averaged over the vehicle population, and
- h_p = hot-soak evaporative emissions of pollutant p in kilograms averaged over the vehicle population (nonzero only for HC).

The first term of equation 1 gives hot-running emissions, the second term gives cold-start emissions, and the third term gives hot-soak evaporative emissions. The hot-running, cold-start, and hot-soak emissions attributable to a specific trip type were obtained by summing the corresponding terms of equation 1 over all trips of the specified type. Total emissions attributable to a trip type were obtained by summing E_p over all trips of the specified type.

In addition to the trip-related emissions of equation 1, each automobile maintained in the Washington area was assumed to produce diurnal evaporative HC emissions regardless of the use it received. Thus, total daily emissions were obtained by summing

E_p over all trips and by adding diurnal evaporations to the resulting sum.

Equation 1 emission factors for both the Washington area and Allegheny County are given in Table 1. Cold-start and running exhaust emissions were estimated from emissions data reported by Automotive Environmental Systems, Inc., (2) and by using methods suggested by Martinez et al. (3). Cold starts were associated with trips that originated at home or at work. Based on results obtained by General Motors (4), 50 percent of the evaporative emissions measured by the federal test procedure (5) was attributed to hot soaks. The other 50 percent was attributed to diurnal evaporations. Average federal test procedure evaporative emissions and crankcase emissions were obtained from Sigworth (6), and speed adjustment factors are from Kircher (7).

RESULTS

Table 2 gives Washington area emissions, VMT, and trip volumes according to trip purpose. Diurnal HC evaporations, which are not related to travel behavior, are displayed separately from the travel-dependent HC emissions. HB work trips cause 35 to 40 percent of automobile emissions, depending on pollutant, and generate more emissions than any other trip purpose generates. Unidentified other trips, whose emissions are nearly as large as those of work trips, and HB shopping trips are next in importance. Within trip-purpose classes, emissions of all pollutants are approximately proportional to VMT.

The effects of cold starts and hot-soak evaporations on the emissions attributable to the various trip purposes are given in Table 3. Cold starts, which are related to trip volumes but not to trip lengths or speeds, cause 21 percent of CO emissions and 13 percent of trip-related HC emissions. Hot soaks, which are also independent of trip lengths and speeds, contribute an additional 20 percent of trip-related HC. Thus, 33 percent of trip-related HC emissions are independent of trip lengths and speeds. The cold-start contribution to NO_x emissions is slightly negative (-2 percent); this indicates that trips beginning with cold starts have somewhat lower NO_x emissions than trips beginning with hot starts. This reflects the high engine temperatures required for NO_x formation. Cold starts are of greater importance for HB work trips than for other trips because HB work trips are the only trips that have cold starts in both the home-to-destination and destination-to-home directions.

The effects of cold starts and evaporations are also shown in Table 4, which gives the emissions attributable to the running portion of trips; 79 percent of CO emissions and 63 percent of HC emissions occur during actual running.

Table 5 gives the grams per mile (kilometer) emission rates of trips in the Washington area together with emission rates obtained from emissions factors in the federal test procedure adjusted for variations in trip speeds (7). The average Washington area CO and HC emissions rates are respectively 9 and 13 percent higher than the federal test procedure rates. This is caused by differences between Washington area travel characteristics and those assumed in the federal test. In the Washington area, 60 percent of trips begin with cold starts; the average trip length is 5.9 miles (9.5 km), and cars travel 19 miles (30 km) per day on an average. In the federal test, 43 percent of trips begin with cold starts, the trip length is 7.5 miles (12 km), and vehicles are assumed to travel 26 miles (42 km) per day. Moreover, the federal test weights each model year's contribution to diurnal evaporative emissions in proportion to that model year's VMT; however, the weights used here are proportional to each model year's prevalence in the vehicle population. Agreement between Washington area and federal test emissions rates is achieved when the Washington rates are adjusted to reflect federal test travel characteristics.

NO_x emissions have no evaporative sources and are relatively insensitive to cold starts. Hence, Washington and federal test NO_x emissions rates are approximately equal.

The distribution of Washington area emissions by time of day for work trips and all trips is given in Table 6. Peak-period trips cause 35 to 39 percent of daily automobile emissions, depending on the pollutant. Peak-period work trips cause 23 to 26 percent

Figure 1. District map of Washington, D.C., area.

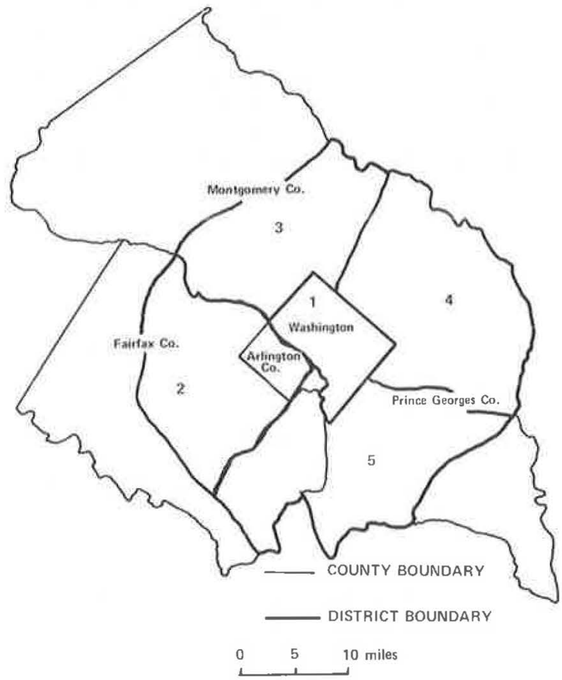


Table 1. Average emission factors.

Pollutant	Factor[a]	Emissions (kg/mile) Washington, D.C.	Allegheny County
CO	e	0.0271	0.0332
	c	0.0723	0.0850
NO_x	e	0.0035	0.0037
	c	-0.0008	-0.0009
HC	e	0.0028	0.0033
	k	0.0001	0.0001
	c	0.0053	0.0061
	h	0.0048	0.0067
	d	0.0062[b]	0.0084[b]

Note: 1 kg/mile = 0.62 kg/km.

[a]As in equation 1.

[b]Diurnal evaporations are in kilograms per vehicle per day.

Table 2. Washington emissions per day, VMT, and trip volumes by trip purpose.

Item	Trips Number	Trips Percent	VMT Amount	VMT Percent	CO Amount (kg)	CO Percent	NO_x Amount (kg)	NO_x Percent	HC Amount (kg)	HC Percent
Trip purpose										
HB work	922,000	29	7,100,000	38	257,000	40	25,300	37	29,400	35
HB shopping	639,000	20	2,560,000	14	95,000	15	9,400	14	12,200	14
HB social-recreational	311,000	10	1,890,000	10	60,000	9	7,000	10	7,500	9
HB school	82,000	3	498,000	3	16,000	3	1,800	3	2,000	2
Other	1,250,000	39	6,700,000	36	215,000	33	24,700	36	27,400	32
All[a]	3,200,000	100	18,700,000	100	643,000	100	68,100	100	78,600	93
Emission										
Diurnal									6,200	7
Total									84,700	100

Note: 1 mile = 1.6 km.

[a]May not agree with column totals due to rounding.

Table 3. Washington cold-start and hot-soak emissions per day by trip purpose.

Trip Purpose	CO Amount (kg)	CO Percent Purpose[a]	CO Percent Total[b]	NO_x Amount (kg)	NO_x Percent Purpose[a]	NO_x Percent Total[b]	Cold-Start HC Amount (kg)	Cold-Start HC Percent Purpose[a]	Cold-Start HC Percent Total[b]	Hot-Soak HC Amount (kg)	Hot-Soak HC Percent Purpose[a]	Hot-Soak HC Percent Total[b]
HB work	67,000	26	10	-740	-3	-1	4,900	17	6	4,400	15	5
HB shopping	23,000	24	4	-260	-3	0	1,700	14	2	3,100	25	4
HB social-recreational	11,000	19	2	-130	-2	0	800	11	1	1,500	20	2
HB school	3,000	18	0	-30	-2	0	200	11	0	400	19	0
Other	34,000	16	5	-340	-2	-1	2,500	9	3	6,000	22	7
All[c]	138,000	21	21	-1,530	-2	-2	10,100	13	12	15,400	20	18

[a]Cold start emissions as percentage of trip purpose emissions.

[b]Hot soak emissions as percentage of total emissions.

[c]May not agree with column totals because of rounding.

Table 4. Washington running emissions per day by trip purpose.

Trip Purpose	CO Amount (kg)	CO Percent	NO_x Amount (kg)	NO_x Percent	HC Amount (kg)	HC Percent
HB work	190,000	30	26,000	38	20,100	24
HB shopping	72,000	11	9,700	14	7,500	9
HB social-recreational	48,000	8	7,100	10	5,100	6
HB school	13,000	2	1,800	3	1,400	2
Other	181,000	28	25,000	37	18,900	22
All[a]	505,000	79	69,700	102	53,100	63

Note: Emissions include hot-running exhaust and crankcase emissions.
[a]May not agree with column totals because of rounding.

Table 5. Washington emissions per mile by trip purpose.

Trip Purpose	CO	NO_x	HC	Avg Miles	Avg mph
HB work	36	3.6	4.1	7.7	20
HB shopping	37	3.7	4.8	4.0	19
HB social-recreational	32	3.7	4.0	6.1	21
HB school	33	3.6	4.1	6.1	20
Other	32	3.7	4.1	5.4	20
All	34	3.6	4.5[a]	5.9	20
Federal test	31	3.7	4.0[a]	7.5	20

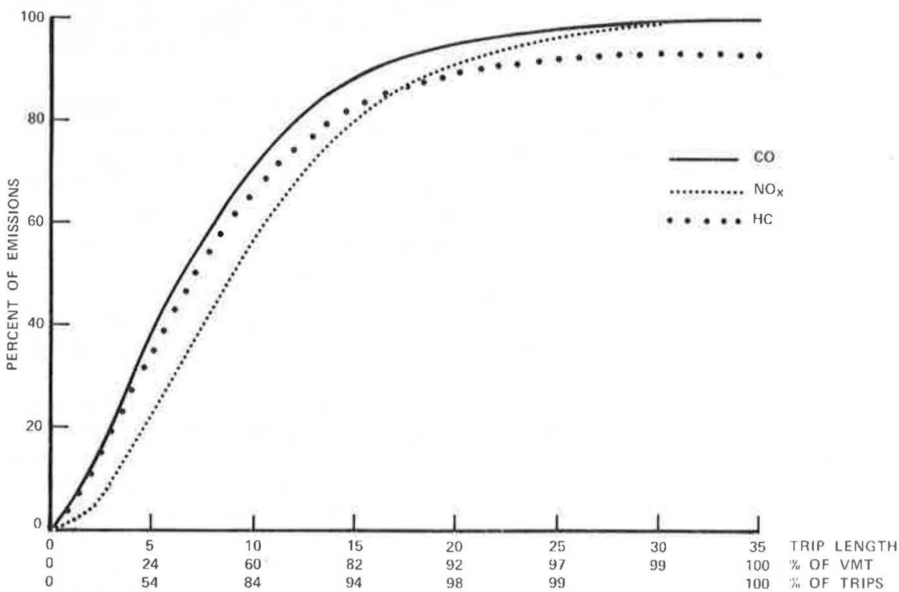
Note: Emissions are in grams per mile. 1 g/mile = 0.62 g/km. 1 mile = 1.6 km.
[a]Includes diurnal evaporations.

Table 6. Washington emissions per day by time of day.

Time	Trips Number	Trips Percent	VMT Amount	VMT Percent	CO Amount (kg)	CO Percent	NO_x Amount (kg)	NO_x Percent	HC Amount (kg)	HC Percent
Peak	1,020,000	32	6,900,000	37	252,000	39	24,500	36	29,400	35
Off-peak	2,180,000	68	11,900,000	63	391,000	61	43,700	64	49,100	58
Peak HB work	570,000	18	4,600,000	24	168,000	26	16,200	24	19,100	23
Off-peak HB work	350,000	11	2,500,000	13	88,000	14	9,100	13	10,300	12

Note: 1 mile = 1.6 km.

Figure 2. Cumulative distribution of Washington, D.C., emissions by trip length.



of daily automobile emissions and about 65 percent of daily work-trip emissions.

The relationship between emissions and trip lengths is shown in Figure 2 by the cumulative distribution of Washington area emissions according to trip length; 53 percent of CO emissions and 50 percent of HC emissions are caused by trips whose length is less than 7 miles (11 km). However, these trips are responsible for only 39 percent of the VMT and indicate that CO and HC emissions per VMT are higher for short trips than for long trips. This is caused by cold starts and evaporations, whose contribution to average emissions per mile (kilometer) increases as trip length decreases, and by the low speeds of short trips compared with long trips in the Washington area [e.g., 4 mph (6.4 km/h) for a 1-mile (1.6-km) trip compared with 22 mph (35 km/h) for a 10-mile (16-km) trip]. NO_x emissions rates, which are relatively insensitive to cold starts and variations in speeds, do not vary greatly with trip length. Thus, only 37 percent of NO_x emissions are caused by trips that are less than 7 miles (11 km) long.

Despite the high CO and HC emissions per VMT for short trips, they have lower emissions per trip than long trips. Trips less than 7 miles (11 km) long, which produce 37 to 53 percent of automobile emissions, account for 69 percent of all trips.

The relationship of emissions to trip origins and destinations was investigated by dividing the Washington area into five districts (Figure 1). District 1 is the city of Washington. Table 7 gives the emissions attributable to trips of all purposes that originate or terminate in each district and the emissions produced by district 1 internal and peak-period trips. Table 7 also gives the same information for HB work trips. District 1 trips for all purposes produce 33 to 37 percent of total automobile emissions. District 1 work trips produce 17 to 20 percent of total emissions or roughly half of all work-trip emissions; peak-period district 1 trips cause 15 to 17 percent of total emissions. Roughly 75 percent of the emissions attributable to trips originating or terminating in district 1 are caused by trips that cross the district boundary. This proportion increases to about 80 percent when only work trips are considered.

COMPARISON OF RESULTS FROM WASHINGTON, D.C., AND ALLEGHENY COUNTY

Table 8 gives aggregate demographic, geographic, and travel characteristics of the Washington area and Allegheny County. The Washington area has more people and cars and a larger geographic area than Allegheny County. Accordingly, Washington has more trips and VMT per day. The average trip is longer and faster in Washington than in Allegheny County; moreover, Washington area cars are somewhat newer than Allegheny County cars and, on average, travel farther per day.

The aggregate characteristics of automobile emissions in Washington and Allegheny County are given in Table 9. Total emissions of all pollutants are considerably greater in Washington than in Allegheny County; this reflects the greater amount of travel in Washington. However, emissions per VMT are lower in Washington than in Allegheny County. This is attributable to several factors. Because cars in Washington are newer, the emissions are cleaner. Thus, the equation 1 emission parameters are lower for Washington than for Allegheny County (Table 1). The higher average trip speed in the Washington area also reduces average emissions per mile (kilometer). In addition, Washington's longer trip length and greater daily VMT per car reduce the contribution of evaporative and cold-start emissions to average emissions per VMT in the region.

The federal test method of computing emissions underestimates them in both Washington and Allegheny County (Table 9). However, the federal test assumptions of a 7.5-mile (12-km) average trip length and 26 miles (42 km) of travel per vehicle per day are more nearly met in Washington than in Allegheny County. Accordingly, the federal test method approximates Washington area emissions better than Allegheny County emissions.

The distribution of emissions in the two regions according to percentages of emissions and trip types is shown in Table 10. Evaporations are less important relative to other emissions sources in Washington than in Allegheny County; this reflects the

Table 7. Geographic characteristics of Washington emissions per day for all purposes and home-based work trips.

Trip Purpose	District	Trips Number	Trips Percent	VMT Amount	VMT Percent	CO Amount (kg)	CO Percent	NO_x Amount (kg)	NO_x Percent	HC Amount (kg)	HC Percent	Avg Miles	Avg mph
All	1[a]	400,000	12	1,220,000	7	64,000	10	4,100	6	7,700	9	3.1	13
	1[b]	391,000	12	2,860,000	15	108,000	17	9,900	15	12,400	15	7.3	17
	1	1,020,000	32	6,630,000	35	237,000	37	23,300	34	28,100	33	6.5	18
	2	830,000	26	5,570,000	30	183,000	28	20,300	30	22,100	26	6.7	20
	3	830,000	26	5,420,000	29	174,000	27	19,800	29	21,400	25	6.5	21
	4	800,000	25	5,350,000	29	168,000	26	19,700	29	20,700	24	6.7	21
	5	759,000	24	5,780,000	31	177,000	27	21,500	32	21,500	26	7.6	21
Work	1[a]	119,000	4	470,000	3	26,000	4	1,600	2	2,900	4	4.0	13
	1[b]	269,000	8	2,170,000	12	84,000	13	7,500	11	9,400	12	8.1	18
	1	428,000	13	3,380,000	18	126,000	20	11,800	17	14,400	18	7.9	18
	2	241,000	8	2,120,000	11	72,000	11	7,600	11	8,300	11	8.8	20
	3	242,000	8	2,110,000	11	71,000	11	7,500	11	8,200	10	8.7	21
	4	221,000	7	2,000,000	11	66,000	10	7,200	11	7,600	10	9.1	21
	5	253,000	8	2,280,000	12	76,000	12	8,300	12	8,700	11	9.0	21

Note: 1 mile = 1.6 km.

[a]Internal trips. [b]Peak-period trips.

Table 8. Aggregate characteristics of Washington and Allegheny County.

Characteristic	Washington	Allegheny County
Population	2,520,000	1,610,000
Area, $miles^2$	870	728
Area of district 1, $miles^2$	61	55
Cars	1,010,000	519,000
Average car age, years	3.4	4.2
Total daily trips	3,200,000	1,720,000
Total daily VMT	18,700,000	7,280,000
Average trip length, miles	5.9	4.2
Average trip speed, mph	20	18
Average daily VMT per car	19	14
Average daily trips per car	3.2	3.3

Note: 1 $mile^2$ = 2.6 km^2. 1 mile = 1.6 km.

Table 9. Aggregate emission characteristics of Washington and Allegheny County.

Pollutant	Washington	Allegheny County
CO		
Total, kg/day	643,000	348,000
Per trip, g	201	202
Per VMT, g	34	48
Per VMT, g, based on federal test	31	42
NO_x		
Total, kg/day	68,100	27,500
Per trip, g	21	16
Per VMT, g	3.6	3.8
Per VMT, g, based on federal test	3.7	3.9
HC		
Total, kg/day	84,700	48,200
Per trip, g	26	28
Per VMT, g	4.5	6.6
Per VMT, g, based on federal test	4.0	5.1

Note: 1 mile = 1.6 km. 1 g/mile = 0.62 g/km.

Table 10. Comparative distribution of emissions by percentages of trips, VMT, and emissions.

Item	Region	Number of Trips	VMT	CO	NO_x	HC
Emission						
Diurnal-evaporative	Washington					7
	Allegheny					9
Hot-soak	Washington					18
	Allegheny					24
Cold-start	Washington	60[a]		21	-2	12
	Allegheny	57[a]		24	-3	12
Trip purpose						
HB work	Washington	29	38	40	37	35
	Allegheny	28	39	39	39	33
HB shopping	Washington	20	14	15	14	14
	Allegheny	14	10	11	10	11
HB social-recreational	Washington	10	10	9	10	9
	Allegheny	8	8	7	8	7
Other	Washington	41	38	36	39	35
	Allegheny	50	43	43	43	40
Trip type						
Shorter than 5 miles	Washington	54	24	38	22	35
	Allegheny	70	33	53	31	49
District 1, all trips	Washington	32	35	37	34	33
	Allegheny	41	40	49	50	43
District 1, work trips	Washington	13	18	20	17	17
	Allegheny	14	23	22	22	19

Note: 1 mile = 1.6 km.

[a]Fraction of trips beginning with cold start.

Table 11. Geographic characteristics of emissions for nonwork trips by percentages of trips, VMT, and emissions.

Region	District	Number of Trips	VMT	CO	NO_x	HC
Washington	1	19	17	17	17	16
	2	18	19	17	19	16
	3	18	18	16	18	15
	4	18	18	16	18	15
	5	16	19	15	20	16
Allegheny	1	27	27	27	28	24
	2	19	19	17	18	16
	3	21	19	18	19	19
	4	12	14	11	15	10
	5	11	13	10	13	10

Note: Percentages refer to travel to or from district. 1 mile = 1.6 km.

greater average trip length and prevalance of evaporative emission controls in newer cars in Washington. The cold-start proportions of emissions are similar in the two regions. Given that all other things are equal, the greater average trip length in Washington would tend to reduce the importance of cold starts there compared with that in Allegheny County. However, the greater prevalence of evaporative emission controls in Washington tends to increase the proportion of emissions attributable to cold starts and approximately cancels the effects of the increased trip length.

HB work, shopping, and social-recreational trips produce a slightly greater proportion of emissions, and other trips produce a slightly smaller proportion in the Washington area than in Allegheny County. Short trips are a considerably more important emissions source in Allegheny County than in Washington; this reflects Allegheny County's relatively short average trip length. Trips less than 5 miles (8 km) long produce roughly half of the CO and HC and a third of the NO_x in Allegheny County; in the Washington area, the proportions are approximately one-third and one-fifth respectively.

Work trips originating or terminating in district 1, the principal city, generate similar proportions of total emissions in Allegheny County and the Washington area. In both regions, district 1 work trips produce more emissions than work trips associated with any other district. However, Washington's district 1 is of considerably lesser importance than Allegheny County district 1 when trips of all purposes are considered. District 1 trips for all purposes produce approximately one-third of Washington area emissions; however, they produce roughly half of Allegheny County emissions. This is a consequence of the relative dispersion of nonwork trips in the Washington area compared with those in Allegheny County (Table 11). Although district 1 trips dominate both nonwork travel and emissions in Allegheny County, all Washington districts are of approximately equal importance for nonwork travel and emissions.

CONCLUSIONS

The results suggest several ways in which measures that are effective in reducing automobile use and emissions in the Washington area are likely to differ from measures that are effective in achieving the same objectives in Allegheny County. One difference concerns the length of trip, to which emissions reduction measures should be oriented. In the Washington area, approximately two-thirds of the CO and HC emissions and three-quarters of the NO_x emissions are caused by trips that are at least 5 miles (8 km) long. Thus, measures designed to affect relatively long trips, such as freeway bus service and bus priority, may be especially useful in reducing Washington area automobile emissions. In Allegheny County, trips less than 5 miles (8 km) long and those longer than 5 miles (8 km) generate roughly equal quantities of CO and HC. Measures serving long trips and measures oriented to short trips, such as jitney and demand-responsive transit service, are both likely to be important in Allegheny County.

A second difference between Washington and Allegheny County concerns the geographic orientation of the trips, to which emissions reduction measures should also be directed. Trips to or from the central area of Allegheny County produce approximately half of the county's automobile emissions and, depending on the pollutant, cause 50 to

60 percent more emissions than trips associated with any other part of the county. Thus, measures whose principal orientation is trips to or from the central area, such as improved radial transit service and restrictions on central-area automobile use, might be highly effective in reducing Allegheny County automobile emissions. In Washington, trips to or from the central area are responsible for only about 35 percent of regional automobile emissions and produce only 10 to 30 percent more emissions than trips associated with certain other parts of the region. Therefore, measures directed at noncentral travel, such as improved intersuburban transit service and extension of automobile use disincentives to the suburbs, could be important supplements to central travel measures in the Washington area. In both Washington and Allegheny County, central travel measures must affect trips between the suburbs and the central area as well as trips within the central area to be effective in reducing regional emissions.

There are also several ways in which the Washington area and Allegheny County are similar. Work trips cause approximately 35 percent of automobile emissions in both the Washington area and Allegheny County. District 1 work trips produce about 20 percent of automobile emissions in both regions. Thus, measures directed primarily at work trips, such as improved peak-period transit service and increased long-term parking fees, may have similar effects on automobile emissions in the Washington area and Allegheny County.

Cold-start and evaporative emissions, which are independent of trip lengths and speeds, can significantly impair the emissions reduction effectiveness of park-and-ride transit in both regions. The impairment is most severe in the case of HC. For example, park-and-ride transit in Allegheny County that requires a 1-mile (1.6-km) home-to-transit automobile trip and serves work trips whose length exceeds 5 miles (8 km) would achieve 62 percent of the reduction in automobile HC emissions that would be achieved by a transit system that had equal ridership but did not require automobile access. In Washington, where trips are longer and evaporations are somewhat less important than in Allegheny County, the equivalent proportion would be 66 percent.

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TOWARD A COMMUNITY IMPACT MEASURE FOR ASSESSMENT OF TRANSPORTATION NOISE

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Despite improvements in techniques for measuring and predicting transportation noise, no one has yet developed a reliable method for identifying the total impact on a community of the noise generated by a proposed transportation facility. A procedure, the noise annoyance impact, is developed for measuring this total impact in a variety of units. In essence, the noise annoyance impact transforms noise measurements for a particular location into a number representing the average impact of such noise on people, multiplies this number by the number of people in that location, and sums this result over the full extent of the area. A sample application, based on two proposed highway alignments for an urban area, used the traffic noise index and the noise pollution level to represent the noise and the data from an earlier survey by the Building Research Station in England to specify the percentage of the population annoyed at a particular reading of a traffic noise index or noise pollution level. The resulting noise annoyance impact was thus expressed as the total number of people annoyed. The noise impact is easy to interpret and, therefore, provides a measure of the total areal impact of noise that can be used effectively in public participation efforts. In addition, the formulation of the noise annoyance impact is mathematically sound. It permits combination of all of the pertinent noise data for the full study area into a single number. Although further research is necessary to specify more accurately the relationship between noise and the percentage of population annoyed or any other measure of average noise impact, the principles of the noise annoyance impact can be applied now.

•RECENT concern about the noise produced by transportation facilities has led to improvements in techniques for measuring and predicting transportation noise. Unfortunately, there have not been similar advances in procedures for incorporating the information from these techniques into some overall assessment of the noise impact of a new facility. It is the aim of this paper to develop procedures that can assess the total community impact of transportation-produced noise.

An assessment technique for noise impact should make use of as much relevant information as possible, and the resulting assessment should be as succinct as possible (a single number would be best). In addition, the technique should be mathematically legitimate and should not multiply or add numbers that represent merely ordinal information. Furthermore, at extreme levels, noise can damage hearing or health; at slightly lower levels, noise remains a source of annoyance or irritation. Presumably, facilities whose noise would cause damage will not be built; therefore, the annoyance factor is of prime concern when noise produced by transportation facilities is assessed. What is needed, then, is a way to measure the total annoyance caused people by the noise from such a facility, over the full areal extent of the impact. A general form for such a measure, the noise annoyance impact (NAI), can be given as

$$\mathrm{NAI} = \int\int f\,[\mathrm{noise}(x, y)]\ \mathrm{pop}(x, y)\,dx\,dy \qquad (1)$$

where

noise(x, y) = appropriate measure of noise at a particular location (x, y);
pop(x, y) = density of people at that location; and
f(noise) = function that describes the annoyance effect of a given level of noise on people and that will change according to the units chosen to express NAI, e.g., total number of people annoyed, total monetary cost of the noise annoyance, or any other logical units.

For example, noise (x, y) might be measured as noise pollution level (NPL) (to be described later), and f(noise) could express the percentage of a population annoyed by a given NPL. Then,

$$a(x, y) = f[\text{noise}(x, y)]\ \text{pop}(x, y) \tag{2}$$

would be the number of people per unit area at a particular location (x, y) annoyed by the noise, and

$$\text{NAI} = \int\int a(a, y)\ dxdy \tag{3}$$

would be the total number of people in the area annoyed by noise.

One assumption is necessary for this approach: The sensitivity to noise of any small population group is similar to that for the full population. This is equivalent to assuming that the population does not self-select through residential locations so that those who are most sensitive to noise do not reside in noisy locations. It is not the same as assuming that all people respond identically to noise; we know the opposite to be true (1). However, since sensitivity does not appear to be related to socioeconomic characteristics but rather to personality traits (2), it is impossible to predict the noise sensitivity of particular groups given presently available population data. Hence it is necessary to assume that the composition of noise sensitivity in any sample population is similar to that of the whole population and that a single function f can be used to represent this. For obvious exceptions to this assumption, e.g., hospitals, a separate noise response function should be used.

The remainder of this paper develops one approach for calculating the number for NAI, discusses several potential measurement scales for noise(x, y) and the function f(noise), demonstrates the use of the measure, and comments on the viability and possible extensions of the measure.

NOISE MEASUREMENT

In this section our twofold purpose is to show that the majority of noise measurement techniques fit into the formula of equation 1 as noise(x, y) functions rather than as f(noise) functions and to discuss several available noise measures before they are introduced as elements of the domain of the function f. Because this is the purpose, we will review the noise measures. If one is to interpret what noise is and what effect it might have, two components must be considered: the acoustic or physical properties and the human reaction to those properties. Ascertaining the former by either direct measurement or calculation is not a problem, and a considerable number of acceptable methods are available. However, selection from among these properties and subsequent combination of them into a single measure that corresponds well to the way humans react to noise are more difficult.

Noise has been defined as unwanted sound, and as sound, direct measurement of its physical properties poses no difficulty. However, for the measurements to be of any value, they must include the intensity, frequency, and duration (or variability over time) of a sound. One commonly used method to establish intensity is the sound pressure level (SPL), expressed in units of decibels and computed by the relation

$$SPL = 20 \log_{10}(p/p_0) \tag{4}$$

where

p = average pressure of a measured sound in a specified frequency band, and
p_0 = reference pressure at the threshold of hearing [usually taken as 0.0002 μbar (0.00002 Pa)].

Thus, when $SPL(p_0) = 0$ dB, sound pressure levels for various pressures may be easily computed. [SPL is not the only measure of noise intensity, but it is commonly used. In fact, Young (3) briefly discusses over 60 noise measurement scales, most of which are variations of the same form.]

The intensity or loudness characteristic depends not only on response to single frequency bands but also on response to wider ranges of frequency. Since sound waves generated by most noise sources do not consist of a single frequency, but rather a range of tones, computational techniques were developed to account for this variation. An early measure by Beranek (in 1936), the speech interference level (SIL), or a later version of it, the preferred speech interference level (PSIL), computed intensity as the arithmetic average of sound pressure levels in three predetermined frequency bands (3). For example, SIL is given as

$$SIL = 10 \log_{10}[(p_1 p_2 p_3)^{2/3}/p_0^2] \tag{5}$$

where

p_i = sound pressure levels in the three specified bands, and
p_0 = reference pressure.

Obviously SIL is identical in form to SPL and has the additional advantage of frequency weighting.

SIL was not the only method to incorporate the concept of frequency into the noise measure; there were at least six methods developed over a 30-year period (from 1930) that attempted to provide even better measures to simulate the response of the human ear to noise. It is not surprising then that this interest in frequency response also resulted in noise measurement instruments that provide direct readout of frequency-weighted noise. When electronic weighting circuits are used, the response of the human ear can be closely simulated if they discriminate against frequencies below 500 Hz and above 10,000 Hz. The most commonly accepted weighting is called the A-weighted scale. Decibel levels referred to in the remainder of this paper will use this weighting, i.e., dBa.

Although the majority of such measures acknowledge that human perception of sound depends on loudness as determined by some combination of frequency and intensity, Kryter argued that annoyance is different from loudness (4, 5). For a study of aircraft noise, he weighted each frequency band differently, thus developing the perceived noise level (PNL) as

$$PNL = 33.2 \log_{10}\left[\sum_i \delta_i (w_i p_i/p_0)^{2/3.6}\right] \tag{6}$$

where

p_i = sound pressure levels in three specified bands;
p_o = reference pressure;
δ_i = 1 for maximum member in summation, 0.3 for octave bands, and 0.15 for third-octave bands; and
w_i = weighting factor for frequency band i.

Equation 6 is quite appealing in its flexibility, particularly when compared with previously available measures. The w_i could obviously be chosen for a wide range of frequency bands and presumably over a wide range of conditions. Unfortunately the data collection and reduction task would be formidable if the measure were to be developed fully. Additionally it still does not account for the third property of sound outlined at the beginning of this section, i.e., duration or time variability.

Almost all noises vary over time, particularly transportation noise. It is apparent that such variations affect the duration of any particular noise level and must be included in noise investigations if a comprehensive examination is to result. The composite noise rating (CNR) appears to be the first attempt at quantifying this effect into a single measure (3) and is given by

$$CNR = L_{eq} + C_{bk} + C_{other} \quad (7)$$

where

L_{eq} = value estimated by $L_{max} + 10 \log (t_e/T)$;
L_{max} = maximum sound pressure in specified frequency band;
t_e = effective duration of L_{max};
T = total sampling time;
C_{bk} = correction for background (ambient) noise; and
C_{other} = correction for other factors, such as time of day.

The CNR provides a measure of the amount by which a relatively steady noise exceeds the background noise, modified by time.

Two modifications have been made to PNL to incorporate the duration of noise. A complex modification resulted in effective perceived noise level (EPNL) (3, 5). A simpler noise and number index (NNI) (7) is given by

$$NNI = \overline{PNL} + 15 (\log_{10} N) - 80 \quad (8)$$

where

$\overline{PNL}$ = average peak PNL observed, and
N = number of aircraft flights.

PNL, CNR, EPNL, and NNI dealt with aircraft noise. None correlated well with annoyance caused by traffic noise. The traffic noise index (TNI) was derived by Griffiths and Langdon (8) to better simulate responses to traffic noise as follows:

$$TNI = 4 (L_{10} - L_{90}) + (L_{90} - 30) \quad (9)$$

where L_i is the noise level (dBA) exceeded i percent of the time. As was the case with the previous four measures, TNI is effective only for the explicit purpose for which it was designed; it does not correlate well with response to other types of noise (e.g., aircraft noise).

The most recent entry to account for variability over time is the noise pollution level (NPL) (9), given by

$$NPL = L_{eq} + (L_{10} - L_{90}) \tag{10}$$

where

$L_{eq} = L_{50} + (L_{10} - L_{90})^2/56$, and
L_i = noise level (dBA) exceeded i percent of the time.

The NPL measure in equation 10 has proved to be the most acceptable measure to date. It provides an annoyance response to fluctuations of noise about a mean level (similar to CNR), is modified by time to account for duration, and appears to simulate response well to all forms of transportation noise.

Regardless of the acceptability of any of the previous measures, none explicitly incorporates the time of day. Obviously an NPL or NNI value will represent more annoyance at 3 a.m. than at 3 p.m. At least two measures have been developed to account for this variation: the noise exposure forecast (NEF), extended from the EPNL (10), and the community noise equivalent level (CNEL), derived for surface transportation noise (11). The formulations of the two are similar. For CNEL,

$$CNEL = L_{50} + 10 \log_{10} N_t - 49.4 \tag{11}$$

where

L_{50} = average noise level of events;
N_t = weighted number of events, e.g., $N_d + 3N_e + 10N_n$; and
N_d, N_e, N_n = number of events during daytime (7 a.m. to 7 p.m.), evening (7 p.m. to 10 p.m.), and nighttime (10 p.m. to 7 a.m.) respectively.

Both CNEL and NEF can therefore represent more comprehensively those aspects of noise that lead to annoyance.

ASSESSMENT OF COMMUNITY IMPACT

Not all recent work has been on measures of noise at one point. A few procedures have been used that attempt to identify the full impact of new facilities over an area. These have not explicitly taken the form of our equation but can be analyzed in terms of it, and the implicit function f(noise) can be identified.

Previous Research

A procedure based on counting the number of households (or people) within a specified critical noise level contour has been used in several studies (12, 13). The noise levels have been measured as discussed earlier in the paper. This approach has the merit of being a concise measure that incorporates areal extent, but it has two major weaknesses. First, the choice of a critical contour must necessarily be arbitrary and may have an unintentionally large influence on relative outcomes, either because of the population distribution or the landscape features affecting noise propagation. For example, assume that one must compare two alternate routes for a roadway and that the contour of 87 NPL has been selected as critical. [This was the value used in the Rand study (12).] Route A is found to involve 100 households inside the 87 NPL contour, and route B involves 150. The choice is obvious. However, suppose that, for one or both reasons mentioned above, there are an additional 100 houses within the 85 NPL contour on route A and only 10 additional houses in the 85 to 87 NPL band on route B. Then, if 85 NPL had been set as the critical value, the decision would be reversed.

The second weakness relates to the form of the function f(noise). As implied by this procedure, it is a zero-one step function. For NPL readings below 87, $f = 0$, and hence the population affected by these noise levels does not contribute at all toward the final measure. For NPL ≥ 87, $f = 1$, and every part of the population is counted. This seems to be an unrealistic form for the function to take and certainly is less justifiable than the assumption about the noise sensitivity of small groups made in the introduction to this paper.

The U.S. Environmental Protection Agency recognized these same kinds of shortcomings and suggested some possible remedies (11) that, to the best of our knowledge, have not been further developed. The Ontario Ministry of Transportation and Communications (MTC) has attempted to overcome these shortcomings with a modification of the same basic approach in which a number of different noise contours are mapped and the affected population in each interval or band is counted. Unless the choice is obvious, because of dominance in all the intervals, individual judgment must be used to combine the counts and their corresponding intervals so that a decision can be made. The modified approach does not fit our equation at all, because it does not result in only one number. The advantage of conciseness is lost, and the relative weighting of all these data becomes arbitrary and implicit.

Proposal

This review of previous and current practice indicates that no one has yet produced a completely satisfactory traffic noise impact measure that incorporates the full areal effect. What is needed is a way to identify the total annoyance caused by a specific transportation project. The following discussion is organized around two questions:

1. What does total annoyance mean?
2. How can the annoyance caused by a specific project be isolated?

A meaningful measure of total annoyance should be grounded in reasonable notions of individual annoyance responses that can be aggregated legitimately and understandably. Two concepts of annoyance responses at the individual level are plausible:

1. Annoyance is a two-valued response, i.e., either one is annoyed or one is not annoyed.
2. Annoyance is a many-valued response, in which increasing degrees of irritation are possible. At the extreme, this concept includes a continuum of annoyance, with an infinite number of possible responses.

The ability to aggregate individual responses legitimately makes certain demands on the kinds of scale (nominal, ordinal, interval, or ratio) used to tally such responses. Aggregation also requires a function that, for a particular measure of noise, will define the impact on persons subjected to that noise. Because response or sensitivity to noise varies considerably for different people, the number given by the function will necessarily be an average or representative response.

Assuming a two-valued individual annoyance response, this average can be easily and legitimately obtained. At any reading of noise(x, y), f(noise) will simply be the percentage of the total population that is annoyed by that noise. The individual response can be measured on a nominal scale, but f(noise), representing aggregate response, will provide a result on a ratio scale, permitting multiplication (by numbers of people) and addition quite legitimately.

The assumption of a many-valued individual annoyance response, although possibly more appealing intuitively, makes aggregation and subsequent calculation considerably more difficult. The standard procedures for collecting data on subjective human responses, such as annoyance caused by noise, rely on ordinal scales (e.g., a semantic differential scale). Arriving at the average response for a particular noise(x, y) reading demands caution when this scale is used. The only legitimate value to use is the median response; use of the arithmetic mean instead of the median response demands that the data be at least on an interval scale. Although ordinal numbers are treated as if they contained interval scale properties, this can be avoided, and a legitimate and representative or average f(noise) can be derived.

Unfortunately, the resulting function cannot be used in the kind of calculation involved in our equation. For such multiplications to be meaningful (much less legitimate), f(noise) must produce numbers on a ratio scale, but the median response values still represent only an ordinal scale. As constructed, our equation implies that 200 people experiencing degree 4 annoyance represent an equivalent impact to 400 people experiencing degree 2 annoyance or 800 people experiencing degree 1 annoyance. Doubling the annoyance measure must imply doubling the severity, or it is nonsensical to multiply populations by annoyance levels.

Although standard subjective response data are ordinal, other kinds of many-valued annoyance response data may be collected that would surmount this problem. For example, a monetary annoyance measure obviously meets the ratio scale requirement and has the additional advantage of being intuitively understandable to respondents. Although such monetary data might be harder to obtain than ordinal data, they seem the simplest way to implement the formula if one prefers to view individual annoyance responses as many valued.

We still have to identify the way in which the annoyance due to a specific project can be isolated. The item of interest is the change in total annoyance caused by the project ΔNAI_j, where j indexes the several alternative projects. Predicting the noise caused by the project alone and calculating NAI from that to represent ΔNAI_j is wrong. Because of the logarithmic scale used to measure sound pressure (equation 4), on which all the noise(x, y) measures are based, noise levels are not directly additive. In fact, if the difference between the SPL produced by two sources is 6 dBA, the total dBA will only be 1 dBA greater than the larger of the two original levels. Noise from one source does not act alone but acts with all other noise sources in the area. Therefore, the project-produced noise must be superimposed on the background noise before NAI is calculated. However, because the background noise is constant for all projects, the impact of the background noise NAI_b need not be computed and subtracted from NAI_j so that the best alternative with respect to noise can be selected. That is, ΔNAI_j can only be obtained by

$$\Delta NAI_j = NAI_j - NAI_b \tag{12}$$

but this calculation need not be performed so that a choice among the projects can be made; however, NAI_b would have to be calculated to obtain some sense of the absolute scale for NAI_j in each instance, for example, to compare noise reductions with the cost of achieving them.

In summary, the proposal, as given in equation 1, is a measure of the impact of noise based on the total number of people annoyed by a specific transportation project. The function f, the core of this proposal, transforms noise levels (which can be measured however desired) into a measure of the average response of population aggregations to that noise, based on the assumptions that (a) individuals differ with respect to their susceptibility to annoyance caused by noise and that (b) any small group of people can be treated as if their noise sensitivity were the same as that of the whole population. Two meaningful units for NAI are total number of people annoyed, based on the supposition that individual response is two valued, and total monetary value of the annoyance, if individual response is many valued.

EXAMPLE OF APPLICATION OF NOISE IMPACT MEASURE

The following example is intended primarily to clarify the previous discussion and to demonstrate the practicability of the NAI measure. Some parts of the example, in particular the noise(x, y) measure used and the form of the function f, are not as strong as they could be and need better empirical evidence before they are used in an actual project.

Study Area

The example is based on a 1.5-mile (2.4-km) section of the Queen Elizabeth Way through Burlington, Ontario, for which a feasibility study had recently been completed for the Ontario MTC (13). Two distinct alignments were considered in that study, as shown in Figure 1. The case study consisted of calculating the NAI of each of the two proposed routes during the peak hour.

The 1973 residential populations (Figure 1) are based on polling subdivisions (courtesy of the Burlington Planning Department). Although these were the smallest areal units for which population figures could be obtained, a rectangular grid of smaller unit area for noise prediction was desirable; therefore, land use maps were used to approximate the residential distribution. Most districts were almost uniformly built on; in these, the population was assumed to be evenly distributed and subdivision totals were divided accordingly. The largest subdivision, in the center of the study, consisted mostly of truck farms. Most of its population was allocated to the few grid rectangles containing housing, and the remainder of the district was given a very small population.

The major contribution to background noise in the area was assumed to come from the secondary streets in that there was no heavy industry nearby. The 1973 AADT data, obtained from the Burlington Traffic Department, were averaged along the several segments of each street shown to produce a uniform one-way volume for the road. The uniform volumes and the range of volumes on the segments of each road are given in Table 1. Peak-hour volumes were assumed to be 10 percent of the one-way AADT. These values will be conservative because flows in opposite directions were implicitly assumed to be zero. Using the uniform volumes simplified calculations considerably and introduced only minor errors except for two roads. Maple Avenue is both close to the Queen Elizabeth Way, so that its contribution to total noise is minor, and runs through the sparsely settled area, so that the error in NAI will be small. Traffic on Lakeshore Road increases from west to east. At the Queen Elizabeth Way interchange, the range is 5,379 to 9,109; therefore, the error is lowest at the most important location. Nevertheless, application of this technique should obviously use the more accurate volumes.

Specific Functions for Noise Annoyance Impact

Two components of our equation need to be specified before it can be used: (a) the best measure for noise at a point and (b) the function for translating this noise measure into an annoyance measure. The earlier discussion of noise measures suggested that NPL was one of the best available, hence it was chosen for noise(x, y). In addition, TNI was also used for comparative purposes primarily because it was originally derived to give the best fit to annoyance data for traffic noise.

Identification of reasonable functions for f(NPL) and f(TNI) was difficult. The decision was finally made to measure NAI as total number of people annoyed primarily because the only remotely usable data were in this form. Therefore, use of that approach here does not mean we necessarily think that the two-valued concept of individual annoyance is better but simply that it is supportable, and data are available. Although the functions are based on the best available data, their derivation, and even some aspects of the original data, are questionable in places and certainly demonstrate the need for further research.

As shown in Figure 2, the functions represent an interpolation and transformation of a diagram (14) that appears to be based on the survey, undertaken by the Building Research Station (BRS) in England, and that led to the development of TNI (8, 15). That survey collected data on a seven-point scale of satisfaction or dissatisfaction with noise. It is not clear which point on such a scale should be considered to be the turning point for annoyance. In other words, data were collected assuming a many-valued concept of annoyance and were later interpreted assuming a two-valued concept. The transformation for getting from the first to the second assumption was not made known (if indeed it can be legitimate).

A further possible drawback to the function of Waller (14) and BRS is that the TNI is probably not mathematically legitimate. The data were collected on a seven-point ordinal scale but were then treated as at least interval-scaled data in the calculation of a regression equation. It is not clear, from available references, whether Waller's graph depends on the TNI calculation or goes back to original data. In either case the first objection definitely holds so that the specific results obtained in this example should not be taken too seriously; however, this is the best available data for such a function and is used here simply for demonstration purposes.

Calculations

For calculation purposes, the study area was represented by a grid of 400 by 1,000-ft (122 by 305-m) cells. The grid orientation was chosen to coincide with the alignment of the majority of the secondary road system. Population was allocated to this grid as described previously.

Based on the traffic flows in Table 1 and known characteristics of the roadways and surroundings, NPL and TNI were predicted for each grid point as follows. The noise from each roadway was calculated by using an interactive computer program adapted at McMaster University from the Michigan version of the method used by Bolt Beranek and Newman, Inc. (16, 17). Possible output from the program included L_{90}, L_{50}, L_{10}, CNEL, TNI, and NPL. The first three of these were used as input to an additional program package, also developed at McMaster University, that added all the noise contributions at each grid point. This program then calculated NPL and TNI, estimated the percentage annoyed from a discrete representation of the curves (Figure 2), multiplied this by population, and summed this result over all grid points for the area. This was done for each of the two alternative alignments.

Interpretation of Results

Although results of the case study are presented here, one must remember the shortcomings discussed earlier and not consider these particular numbers to be decisive for the study area. The final results indicate little real difference between the noise impacts of the two alignments. For the westerly alignment route A, NAI is 2,665 based on NPL as the measure of noise; NAI_B is 2,636. The difference of 29 people is not particularly significant compared with the total study area population of almost 10,000. Astonishingly, when TNI was used as the noise measure, the difference between NAI_A and NAI_B was almost identical (1,842 versus 1,812), although the total numbers are quite different from those based on NPL.

Areal disaggregation of the total NAI is quite simple, based on the original grid representation of the data, and permits closer scrutiny of the locations most strongly affected. Figures 3 and 4 show disaggregated representations of NAI_A and NAI_B (based on NPL). In addition, representative intermediate results have also been plotted for route B: L_{10} in Figure 5; NPL in Figure 6; and f(NPL), the percentage annoyed at each grid point, in Figure 7. Figures 3, 4, 5, 6, and 7 are shown as three-dimensional representations for ease of interpretation but could as easily have been presented in the standard contour format.

Some of the drawbacks of the approaches based on counting houses within critical

Figure 1. Study area, showing population.

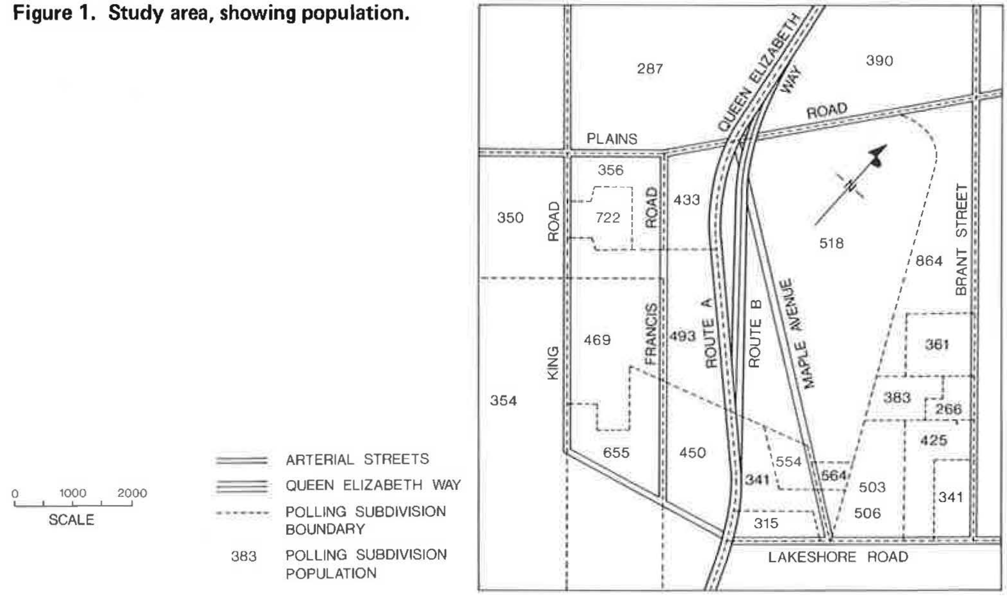

Table 1. 1973 AADT for roads in study area.

Road	AADT Average	AADT Range
King Road (Highway 2)	2,625	1,833 to 3,599
Francis Road	1,069	856 to 1,320
Queen Elizabeth Way	48,270	47,350 to 51,050
Maple Avenue	3,383	990 to 7,604
Brant Street	7,797	6,630 to 9,250
Plains Road	7,459	6,620 to 9,569
Lakeshore Road (Highway 2)	7,594	4,371 to 11,550

Figure 2. Functions of TNI and NPL.

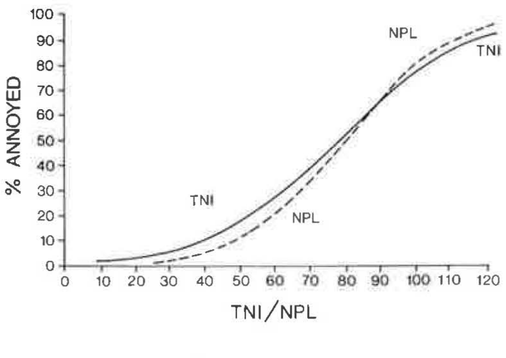

Figure 3. Population annoyed based on noise pollution levels, route A.

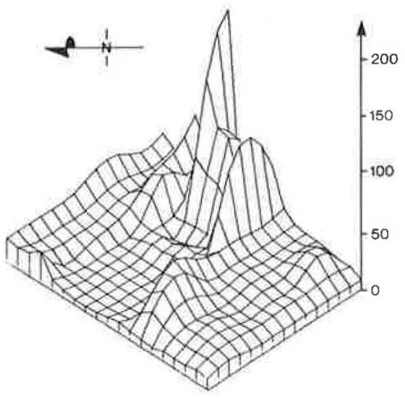

Figure 4. Population annoyed based on noise pollution levels, route B.

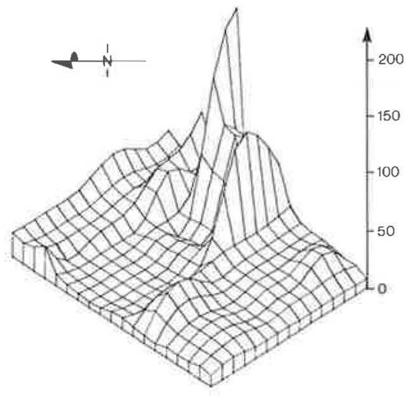

Figure 5. L_{10} noise levels, route B.

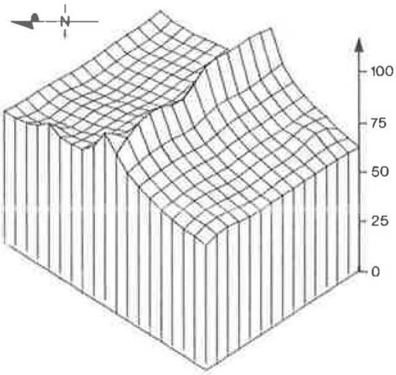

Figure 6. Noise pollution levels, route B.

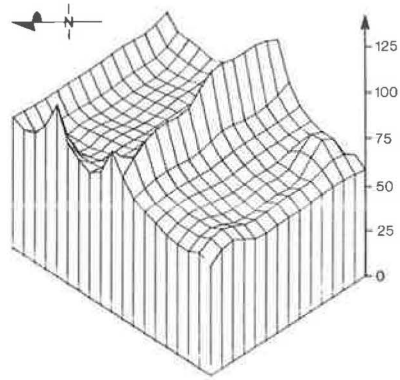

Figure 7. Percentage of population annoyed at each grid point based on noise pollution level, route B.

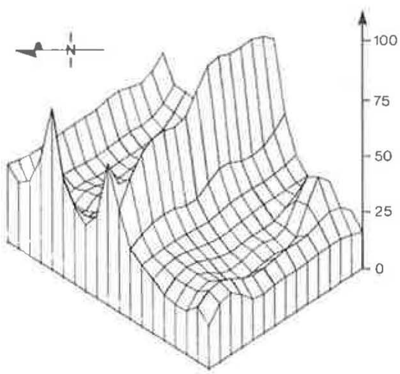

Table 2. Results for modified Ontario Ministry of Transportation and Communications approach.

Range	Contour Interval (dBA for L_{10})	People Affected	
		Route A	Route B
Lowest	70 to 74	332	442
Intermediate	75 to 79	229	12
Highest	80 and over	358	365

contours can be demonstrated with these intermediate results in conjunction with the population data. The approach of the Ontario MTC referred to earlier used an L_{10} of 70 dBA as the critical contour. Route A affects 919 persons within that contour; route B affects 819. If one is certain of the critical contour selection, then route B is obviously the better choice. However, if uncertainty exists about the critical contour, the modified Ontario MTC approach might be preferable (Table 2). The additional information (Table 2) appears to make the choice harder rather than easier. Using NPL data to draw the contours, as done in the Rand study, gives similarly confusing results. For a critical contour of 87 NPL (the value used by Rand) routes A and B affect similar numbers of people (370 and 365 respectively). If a different critical level is used, the choice of alternative will change. For example, at 80 NPL 436 and 378 people are affected (B is better); however, at 95 NPL 244 and 335 people are affected (A is better). Such potential ambiguity in a decision procedure provides a strong incentive for using a measure such as the NAI, which can incorporate the fact that different numbers of people are affected by different noise levels.

CONCLUSIONS

The limitations of this particular example are obvious. We used 1973 population and traffic data for what are actually future roadways. The simplifying assumptions for traffic flow have probably distorted the results somewhat. The representations of f(NPL) and f(TNI) used here are not rigorous and might be different for different land uses or for different times of day. However, all of these limitations can be overcome with more time or personnel to carry out calculations, with additional research on people and noise response, or even with better use of existing data. If such problems cannot be overcome, particularly those relating to the function transforming noise measures into annoyance, any efforts to incorporate noise pollution into an evaluation procedure may be counterproductive or misleading because one is unlikely to be clear about what is being measured.

The general approach is nevertheless persuasive: It is well suited to visual display, easy to interpret, and intuitively meaningful. Additionally, the calculations involved are quite straightforward and easy to follow and permit the inclusion of such a measure in public participation meetings. In fact, it is probably easier to understand the significance of this measure than of any of the others currently in use. The final advantage is that the general approach is applicable to any kind of noise source and that this, in turn, permits comparison among different modes of transportation, a task for which few of the existing noise measures are reliable. However, one shortcoming of the discussion of this proposed community noise impact measure, in both the example and the theory, should be brought out. As presently defined, NAI is a static measure, concerned with noise during 1 hour of an average day of 1 year. This is inaccurate in several respects: Noise levels vary over the day; population varies over the day, in terms of physical presence of people; and, in the long run, both population and traffic are sure to change (and likely to increase). A more complete noise impact measure should probably be expressed as

$$\mathrm{NAI} = \sum_t n(t)\, d(t) \cdot \int\int\int f[\mathrm{noise}(x, y, h, t)] \cdot \mathrm{pop}(x, y, h, t)\, dx\,dy\,dh \tag{13}$$

where

- x and y = spatial coordinates;
- h = hours of the day;
- t = years into the future;
- d(t) = some discounting factor, indicating that future noise is not equal in importance to present noise; and
- n(t) = number of traffic days to be considered in the year, which may change if the workweek changes.

Obviously, several of the functions needed to carry out this complete analysis are not known and would be hard to specify. Some of them are not out of reach, however, and would be worth pursuing.

Consider, for example, what is needed to treat noise impacts over a full day rather than simply during the rush hours. The noise prediction techniques call for traffic volume and composition among other variables. Although a complete prediction of off-peak travel would be too much to expect, 24-hour volumes could be distributed over the day roughly as is currently done or in some other way to arrive at acceptable estimates. If the traffic can be estimated, then noise can be estimated as well. Population fluctuations over the day can also be estimated on the basis of generalizations about family behavior, e.g., work, school, and shopping trips. If this is done, it may well turn out that the noise impact of a particular road is less than anticipated because the population is smallest when the noise is worst. Thus, incorporating the fact that population fluctuates over the day may prove sufficiently important to warrant an investigation. A variable measuring the stage in the life cycle of adjacent populations may also be necessary to more clearly delineate likely daily population movements.

Even more information is needed to treat changing noise impacts over a span of years, and the effect may be more important than that of the daily cycle. Not only traffic will increase, but the population will change as well. Areas that were at one time open fields will contain housing, the density in single family areas may increase, and residential land may be converted to industrial activities. Even if traffic and noise levels were to remain constant, the impact would certainly change. The problems involved in predicting these data are not to be minimized. With a great deal of effort we can predict, without a great deal of accuracy, traffic levels 15 to 20 years from now. What the traffic will be during the intervening years is extremely hard to guess at, even if the terminal forecast is right. Should one use straight-line, exponential, or logistic interpolation? Likewise, we can produce a reasonable estimate of land use patterns in the terminal year; in fact, this was probably done as part of the traffic forecast. But when will certain land use changes occur during the intervening period?

These problems, however, are not unique to noise impact measurement. They are the same problems that still face any transportation planning effort. When solutions to them are found, they can be used to extend our ability to evaluate transportation noise. It is not necessary to wait for these developments, however. The principles of the noise annoyance impact measure developed in this paper can be applied now to bring noise impact measurement to the same state as the more advanced parts of transportation planning.

ACKNOWLEDGMENTS

We would like to thank the Ontario Ministry of Transportation and Communications for permission to use the noise study data for the example application and the consulting firm of McCormick Rankin and Associates for their assistance in obtaining those data. Special thanks are due Jim Stewart for preparing the example results and report figures.

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PREDICTION OF WAYSIDE RAILROAD NOISE

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The recent trends in the revitalization of rail transport in this country have resulted in increased interest in the use of rail rapid transit systems in our cities and high-speed surface rail links between major population centers. Included in the technology assessment of new and improved rail service will be the associated environmental problems, including potentially serious wayside noise problems. The solution to the railroad noise problem requires a valid technique for prediction of wayside noise to assess the benefit of various noise control strategies. This paper describes a graphic method for use when the geometry is rather simple and a computer program for use in situations when track and terrain geometry are complicated.

•RECENT trends in the revitalization of rail transport in this country have resulted in increased interest in the use of rail rapid transit systems in our cities and high-speed surface rail links between major population centers. Indications of revitalization are as follows:

1. Rail rapid transit extensions and improvements are occurring in the nine North American cities that have such systems, and at least five new rapid transit systems are in the planning and engineering stages;
2. Commuter lines are improving rolling stock and planning new extensions; and
3. Railroads in the 17-state northeast and midwest regions have recently been reorganized, and this has focused attention on the future plans of the U.S. Railway Association, such as a response to the need for a high-speed rail line in the densely populated Boston-Washington, D.C., corridor.

Incorporated in the technology assessment of new and improved rail service will be the associated environmental problems, including the serious problem of wayside noise. We can look to experience abroad for indications of the potential problem of noise from high-speed railways. Public criticism of the excessive noise levels associated with the high-speed Shinkansen trains [130.5 mph (210 km/h)] has caused the Japanese National Railways to embark on an extensive noise control program (1). Environmentalists and engineers in Great Britain are concerned about the potential public outcry against the noise from the new high-speed trains that are planned to link England and France through the English Channel tunnel (2). At the recent International Symposium on Transportation Noise at the University of Southampton, England (3), much discussion was directed toward predicting the noise in the environment after the introduction of high-speed trains capable of speeds of 150 mph (241 km/h) or greater.

Concern about the quality of the environment is no less strong in the United States than it is abroad. The Noise Control Act of 1972 has virtually mandated the consideration of the noise effects of any major improvement in rail service. Moreover, the transportation industry is vitally concerned with patron and public acceptance of new rail vehicles and the location of new rail corridors. Excessive noise will detract from the acceptability of such improved service.

SOLUTIONS TO RAILROAD NOISE PROBLEM

Solutions to the problem of wayside railroad noise can be approached in three ways. The first approach is through the control of noise emission by railroad vehicles. This can be accomplished through noise control engineering applied during the design of all components of new locomotives and cars. The recently proposed U.S. Environmental Protection Agency (EPA) regulation on railroad noise is an example of pressure from the federal level to control noise emission levels from railroad vehicles. The second approach involves the control of noise in the community through use of careful land use planning and zoning practices, upgrading of the noise sections of building codes for proposed structures, and funding of noise control treatments to existing structures. The third approach involves track and right-of-way location as a means of minimizing the noise impact of new or improved rail lines. Two of these three approaches require a valid wayside noise prediction technique to assess the benefits of various noise control strategies.

RAILROAD NOISE COMPARED WITH HIGHWAY NOISE

It is worthwhile to compare the characteristics of wayside railroad noise with those of the other major source of noise from surface transportation, vehicles on a highway. The differences are rather obvious. Railroad noise is intermittent, but highway noise tends tends to be nearly continuous. The frequency spectrum of the noise from vehicles in each case is different. For railroad noise, the measure of community annoyance is related to the maximum noise level of single events and depends on the number of events; for highway noise, community reaction can be related to a longer term statistical measure such as the level exceeded for 10 percent of the noisiest hour (4).

Despite these essential differences, a number of similarities exist among the characteristics of railroad noise and highway noise, and these have important implications in the proposed methods for predicting noise in the community from railroad operations. In both cases, a well-defined corridor exists along which the noise is generated. The geometries along the corridor in each case are similar: a curvilinear path at grade, in cut, elevated, or depressed. Moreover, noise propagation characteristics in each case have many similarities: Shielding effects of barriers, ground and vegetation effects, and atmospheric effects can be computed similarly because in both cases the noise source is relatively close to the ground surface. More importantly, the mean energy level or equivalent noise level L_{eq} is a significant measure of noise from both sources and can be related to the quality of life in the neighboring community in both cases (5). These similarities between railroad noise and highway noise enable the use of a wayside noise prediction technique for railroads in which the final parametric dependence is similar to that of highways.

GRAPHIC TECHNIQUE TO PREDICT WAYSIDE NOISE FROM RAILROADS

Prediction techniques do exist for predicting the time dependence of the wayside A-weighted sound level during a train passage in an open area along a straight section of track (6, 7). For environmental impact analyses, one wants to be able to account for the geometry of the terrain (e.g., curves in the track, wayside barriers), the frequency of the train passages, and the length of the trains and to use the method to construct contours of equal noise impact.

A technique is presented below that may be used to predict the noise at a point (in terms of L_{eq} or L_{dn}, day-night noise level) near an aboveground rail right-of-way. Contours of equal noise level can be constructed by making calculations at several points along lines perpendicular to the right-of-way and then by fitting in the proper curve by interpolation. This method may be used when the geometry is not very complicated.

The basic concepts of this technique are as follows:

1. To divide the rail right-of-way into a number of straight-line segments (the train speed and track condition should be the same along the entire length of each segment),
2. To calculate the single event noise exposure level (SENEL) due to the passage of a single two-axle truck over each segment [a truck can be treated as a point source for wayside locations more than 20 ft (6 m) from the track],
3. To account for the attenuation of the noise from any segment blocked by a barrier,
4. To add up the SENEL values for all of the segments, and
5. To determine L_{eq} by accounting for the number of truck passages (+10 long N) and the period of exposure (-10 log T).

A review of available noise data for many systems was performed as part of an investigation of wheel-rail noise for the Transportation Systems Center of the U.S. Department of Transportation (8). These data, normalized to correspond to the pass-by of a single car at 50 ft (15.2 m), are shown in Figure 1. For good systems (i.e., systems that report either that they grind their track or that their track is very well maintained) on welded track, the peak pass-by noise level is given by

$$L_A = 60 + 30 \log (V/15) \qquad (1)$$

where V is the speed in miles (kilometers) per hour.

Based on the above information, the noise level from a truck passing along a straight-line segment can be approximated by

$$L_A(t) = 58 + 30 \log \frac{V}{15} - 10 \log \frac{vt^2 + d^2}{50^2} + \Delta \qquad (2)$$

where

V = speed in miles (kilometers) per hour,
v = speed in feet (meters) per second,
t = time in seconds,
d = perpendicular distance from an observation point to a rail segment in feet (meters), and
Δ = catchall parameter to account for track condition (e.g., for good bolted track, Δ may be +4 dB).

Figure 2 shows how d is measured; the time t is taken to be zero at the point of closest approach to the observation point.

SENEL for the passage of a truck along a segment is as follows:

$$\text{SENEL}_i = 10 \log\left(\int_{t_1}^{t_2} 10^{L_A(t)/10}\, dt\right) \qquad (3)$$

where i is used to denote the i th segment.

Substituting equation 2 into equation 3 gives

$$\text{SENEL}_i = 23 + 30 \log V_i + \Delta_i + 10 \log \frac{50^2}{d_i v_i} \theta_i \qquad (4)$$

where $\theta_i = \tan^{-1}(vt_2/d) - \tan^{-1}(vt_1/d)$, the angle in radians from the observation point subtended by the rail segment (Figure 2).

The energy equivalent noise level at a fixed observation point is then given by

$$L_{eq} = 10 \log \left(\sum_i 10^{SENEL_i/10} \right) + 10 \log 2N - 10 \log T \tag{5}$$

where N is the number of train car passages in time period T in seconds, and the summation is over the various segments that make up the right-of-way.

The assignment of a value to the parameter Δ requires some judgment. For example, for a well-maintained bolted track, Δ may be +4 dB; for a steel elevated structure, Δ may be +15 dB. Portions of track behind barriers should be treated as separate segments, and the noise reduction should be calculated separately by standard techniques (9) and lumped into the Δ term.

COMPUTER-AIDED COMPUTATION METHODS

To fully assess the noise from rail operations, one needs a valid method for predicting wayside railroad noise in situations with complicated track and terrain geometry. Such situations call for computer-aided methods such as those available for use by highway engineers (10, 11). One of these (10), the Transportation Systems Center (TSC) highway noise computer program, authorized for use in environmental impact statements by the Federal Highway Administration, is currently being modified by Bolt Beranek and Newman, Inc., for use in railroad noise prediction by some rather basic changes in the input parameters for the noise source. These parameters include source height, source spectrum, and a change in the rate of vehicle passage to correspond to the speed and length of trains. An additional change has been incorporated to account for the effect of barriers on source spectra other than trucks and cars, but the strong point of this computer program, its geometry subroutines, remains. Thus, track geometry, barrier segments, and ground absorption strips can be input in the usual way. The output of the program gives the equivalent A-weighted noise level L_{eq} for the period of time under consideration at any number of receiver points. From such information, equivalent noise level contours can be drawn by interpolation.

An example of the use of the modified TSC program is shown in Figures 3, 4, and 5. A hypothetical terrain and track configuration is assumed for analysis (Figure 3) and features a tunnel, a steel bridge, and an area of land shielded from the track by a natural landform barrier. Two parallel tracks are assumed to carry one train in each direction in the hour of interest; each train consists of two 3,600-hp (2685-kW) road locomotives at throttle 8 and pulls 40 loaded freight cars at a speed of 33 mph (53 km/h).

The terrain and track configuration and the locations of receiver points are modeled as shown in Figure 4. As in the original TSC highway noise computer program, the receivers and the endpoints of track segments and barrier segments are located by coordinates: z-coordinate relative to the ground level and x- and y-coordinates based on arbitrarily chosen axes. All input source spectra were taken from the Serendipity Inc., report (6).

The predicted equivalent A-weighted sound levels L_{eq} from this hypothetical example are shown as contours in Figure 5. The shielding effect of the natural barrier is shown in the reduced noise levels in the bottom left side of the figure. Another result worth noting is the widened 80-dB equivalent sound level contour region in the vicinity of the steel bridge.

CONCLUSIONS

Although initial evaluation of the program has only just begun, the potential usefulness

Figure 1. Noise from welded-track systems normalized to single car at 50 ft (15.2 m).

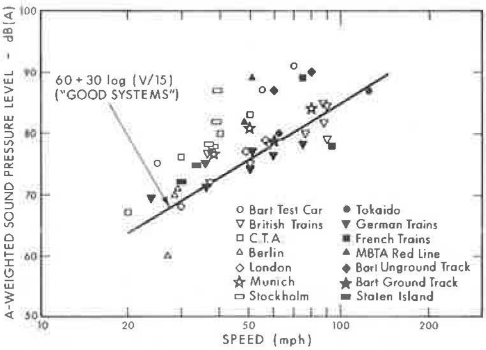


Figure 2. Geometry for short method.

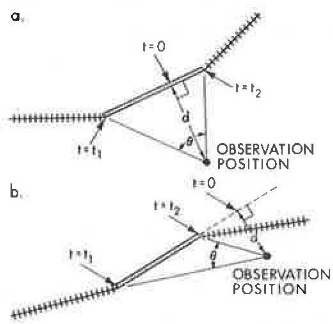


Figure 3. Terrain for rail model example.

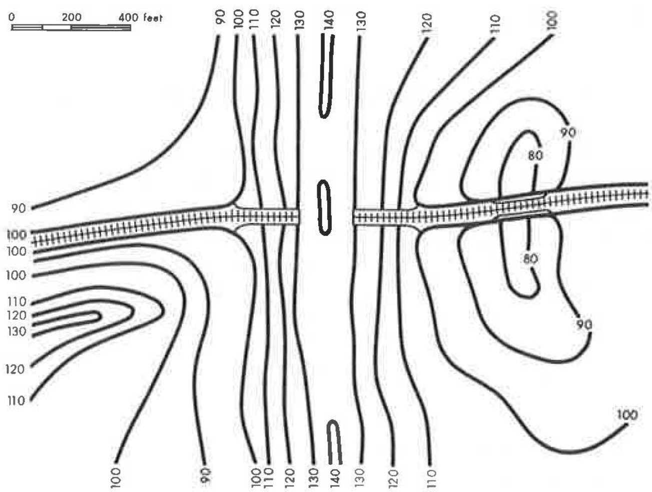


Figure 4. Computer input geometry for rail model example.

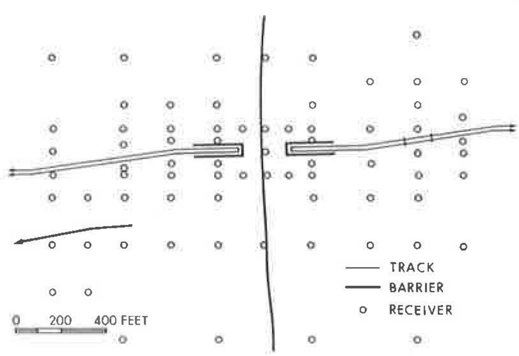
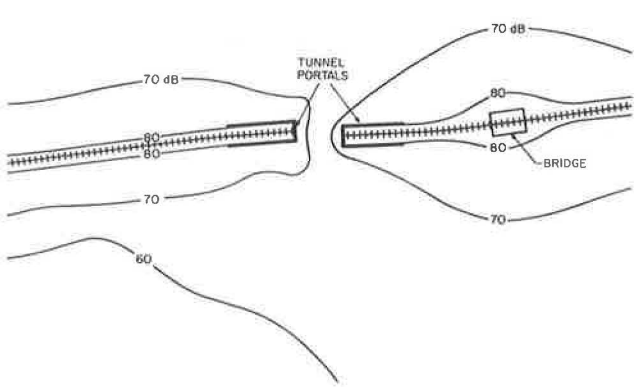


Figure 5. Predicted railroad equivalent A-weighted sound level contours.



of the approach is already evident in problems such as the noise analysis of joint railroad and highway corridors. Additional features, such as inclusion of enough track segment coordinates to obtain a time history of a single pass-by of a train, could make the program even more useful in applications. Moreover, for noise control purposes it is useful to know which segment of track is critical in contributing to the noise at a given receiver. Finally, given the critical segment of track, one wants to know the effect of various noise control measures, such as barriers, in controlling the noise from that segment. A number of these features have already been incorporated in the computer program recently developed by Bolt Beranek and Newman, Inc. (11). Should this computer program be similarly modified for railroad noise prediction, engineers would have at their disposal a useful tool for environmental noise analyses of various transportation alternatives.

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EVALUATION AND MODIFICATION OF TRAFFIC NOISE PREDICTION PROCEDURE FOR KENTUCKY HIGHWAYS

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Approximately 270 recordings of noise levels were obtained at 39 highway sites and compared with the predictions of noise levels based on the procedure given in a National Cooperative Highway Research Program report on highway noise. The measured noise levels were computed in terms of the A-weighted L_{10} value (level exceeded 10 percent of time) and then compared with the predicted noise levels. A significant discrepancy was found between predicted and measured noise levels. Generally, the predicted values exceeded the measured values. Average error per location was 4.8 dBA; the maximum error was 13 dBA. A nomograph was devised to correct the predicted value; this nomograph involves observer-roadway distances, truck volumes, and automobile speeds. Application of the correction factors reduced the average error by 60 percent to 1.9 dBA. Based on these findings, the nomograph was approved by the Federal Highway Administration for use in predicting noise levels in Kentucky.

•POLICY and Procedure Memorandum 90-2 of the Federal Highway Administration stated that all highways constructed after July 1, 1972, must conform to specific design noise levels. To predict future noise levels of highways, a noise prediction procedure has been used. The procedure provides for the determination of the L_{10} noise level (level exceeded 10 percent of the time) based on factors such as observer-roadway distance and shielding. The procedure has not been thoroughly validated, and questions remain about its accuracy. If discrepancies do exist, adjustment factors may need to be applied to more accurately forecast noise levels.

PROCEDURES

To evaluate the currently used noise prediction procedure required that field noise recordings be obtained and compared with noise levels estimated from the prediction model. All recordings were taken at locations with zero grade so that the observer was level with the roadway and there was no shielding to reduce the number of variables that might affect accuracy of the prediction. Figure 1 shows a typical recording site. It was considered essential that gradient, vertical elevation, shielding, element, and interrupted adjustments be evaluated separately from the basic situation—that is, a straight, level section of roadway on unobstructed terrain. The only exceptions to these criteria were some locations in downtown areas, chosen because of high-volume, low-speed traffic, where it was necessary to use the interrupted adjustment because of the high number of traffic signals. Therefore, the only data required to predict noise level were the distance from observer to roadway, surface type, and car and truck volumes and speeds. Predicted noise levels were determined by using the procedure given in a National Cooperative Highway Research Program report (1). The procedure is now being used by the Kentucky Bureau of Highways (2).

Noise recordings were made by using a Bruel and Kjaer precision sound-level meter and strip-chart recorder. Noise recordings (each 10 min long) were made at 39 locations by using the A-weighting network in the meter. A total of 270 recordings were obtained. Use of the strip-chart recorder offered certain advantages: The observer

Figure 1. Typical recording setup.

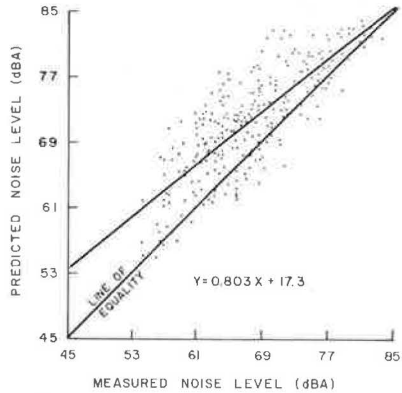


Figure 2. Predicted versus measured noise levels.

could note effects of any unrelated influences such as wind and airplanes, could adjust or disregard the section of the measurement affected and could continually check for agreement between the meter indication and the recorded measurement. From the 10-min recordings, noise levels at intervals slightly greater than 1 sec were determined in the laboratory by using a digital data reduction system. The output was punched onto computer cards through direct coupling with a card punch unit. The L_{10} noise level, the standard for federal limitations on allowable traffic noise, was computed with a simple computer program. The measured L_{10} noise level was then compared with the predicted level.

FINDINGS

The primary objective of this study was to determine whether a significant discrepancy exists between predicted and measured noise levels. Figure 2 shows that the prediction procedure tends to yield higher values. The average error per location was 4.8 dBA, the maximum error was 13 dBA, and the differences were significant at the 0.01 level (probability = 99 percent) (3).

To determine the reason for this discrepancy, we prepared several computer plots (Figure 3). Differences between predicted (uncorrected) and measured noise levels were plotted against several variables that affect noise level, and an optimal linear fit was determined. The variables considered were

1. Observer-roadway distance,
2. Total volume,
3. Car volume,
4. Truck volume,
5. Ratio of car volume to truck volume,
6. Car speed,
7. Truck speed, and
8. Percentage of trucks.

In Figure 3, the plot of observer-roadway distance shows that for short distances the prediction procedure usually yielded higher values than measured values. As the distance increased, the error decreased until the predicted values were below measured values at greater distances.

A nomograph was used to correct the predicted noise levels. A combination of variables should be considered when the corrections are made. For example, an observer-roadway distance of 50 ft (15 m) yields a predicted value that is too high at locations with low truck volumes. The nomograph should permit a reduction of values

Figure 3. Prediction procedure error as function of several variables.

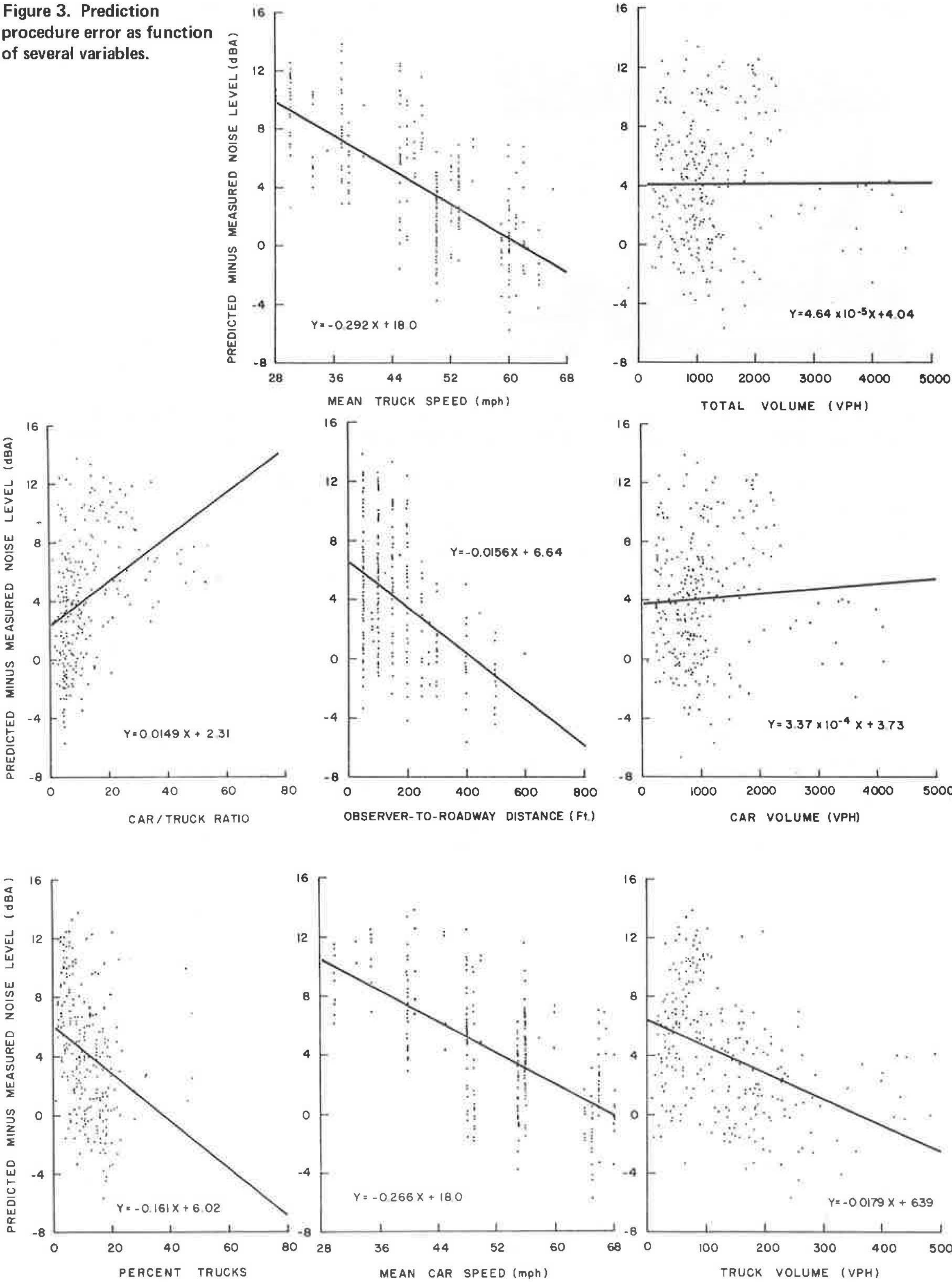
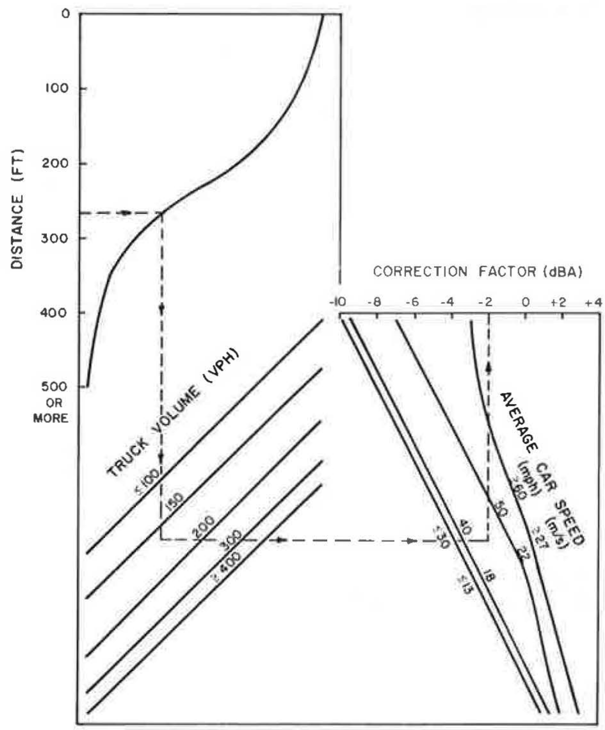


Figure 4. Prediction correction factor nomograph.



at that distance for locations with low truck volumes, but no correction should be made for locations with high truck volumes. A small value should be added for very high volumes. Similar corrections should be made for other variables.

Variables that showed a definite relationship to the prediction procedure error were selected (Figure 3). These variables were then used in various combinations for preparation of trial nomographs. The nomograph that yielded the greatest overall reduction in error is shown in Figure 4. Observer-roadway distance, truck volume, and car speed must be known to determine correction factors from the nomograph.

The following example illustrates use of the nomograph shown in Figure 4. A level, straight, four-lane roadway with a normal surface has a truck volume of 150 vehicles per hour (vph), a car volume of 500 vph, an average truck speed of 40 mph (64 km/h), and a mean car speed of 50 mph (80 km/h). Noise readings are taken at 200 ft (61 m), and there are no barriers or traffic interruptions, such as traffic signals.

The prediction procedure yields a final L_{10} value of 70.8 dBA. To determine the correction from the nomograph, find the distance of 200 ft (61 m) on the scale in the upper left corner of the nomograph. Draw a horizontal line until it intersects the curved turning line. Then draw a vertical line downward to the lines that represent truck volume. Where the vertical line intersects the point that represents the truck volume of 150 (interpolation is necessary in many cases), a horizontal line is then drawn to the lines representing mean car speed. Where the horizontal line intersects the line for car speed of 50 mph (80 km/h) (interpolation is again necessary in many cases), draw a vertical line until it intersects the scale that provides the correction factor. Read the correction factor of -3.2 dBA, and add it (algebraically) to the 70.8 dBA obtained from the prediction procedure. Thus, the corrected value is 67.6 dBA.

Correction factors were obtained for each of the 270 recordings to determine the predicted (corrected) noise levels. Results are shown in Figure 5. The optimal linear fit of the points lies very close to the 45-deg line, which represents the line where predicted noise levels equal measured noise levels. Plots were also made of variables involved versus error in corrected noise levels (Figure 6). As may be seen, the optimal

Figure 5. Predicted (corrected) versus measured noise levels.

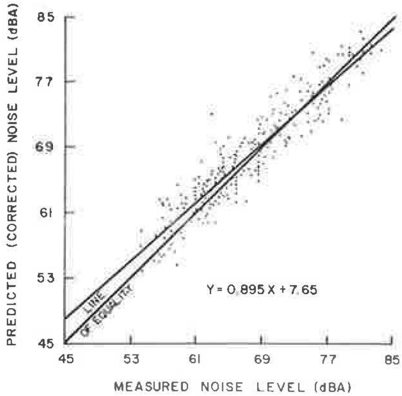
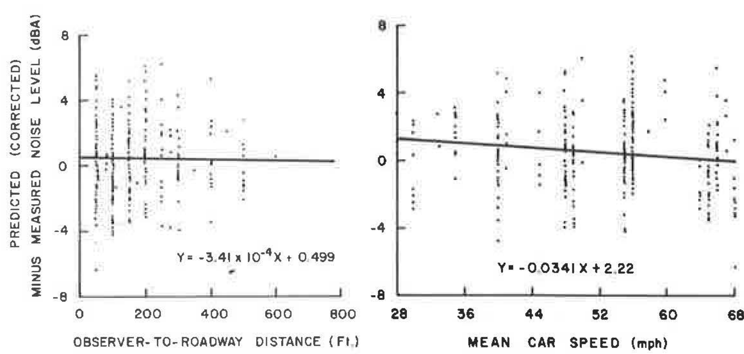
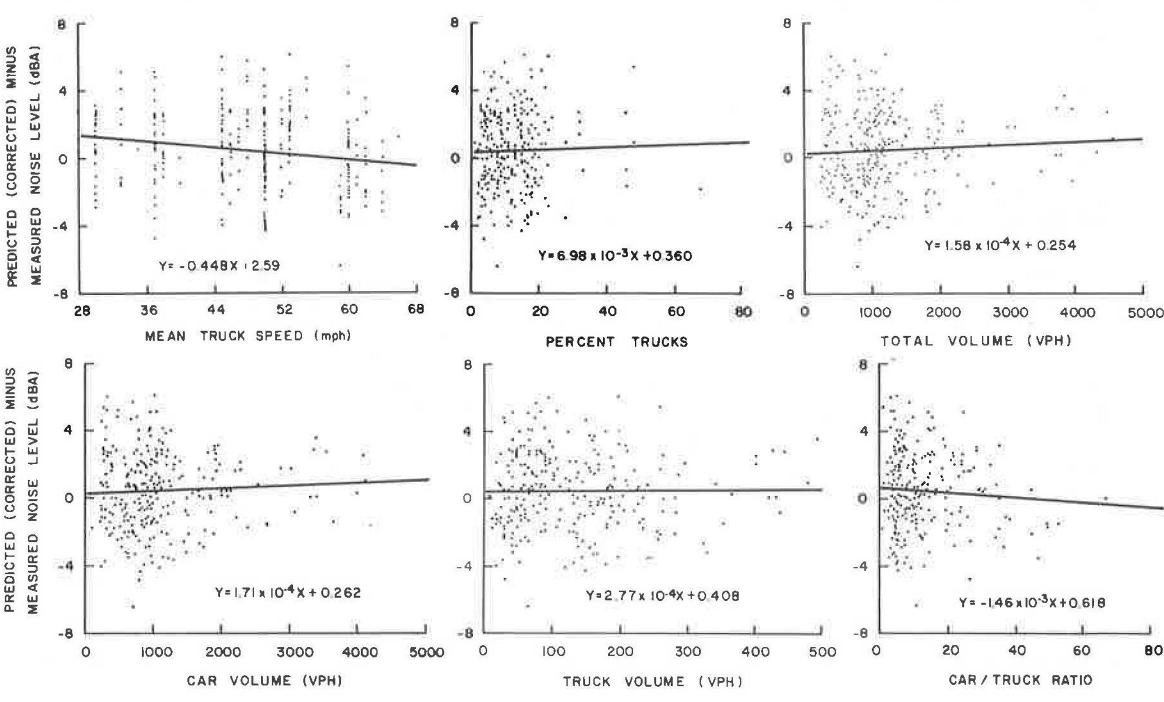


Table 1. Distribution of errors.

Difference Between Predicted and Measured Noise Levels (dBA)	Locations Before Correction		Locations After Correction	
	No.	Percentage Exceeding Noise Level	No.	Percentage Exceeding Noise Level
0 to 0.9	38	100.00	78	100.00
1 to 1.9	41	85.93	67	71.11
2 to 2.9	22	70.74	74	46.30
3 to 3.9	25	62.59	26	18.89
4 to 4.9	26	53.33	15	9.26
5 to 5.9	21	43.70	7	3.70
6 to 6.9	29	35.93	3	1.11
7 to 7.9	14	25.18	0	0
8 to 8.9	9	20.00	0	0
9 to 9.9	13	16.67	0	0
10 to 10.9	17	11.85	0	0
11 to 11.9	8	5.56	0	0
12 to 12.9	5	2.59	0	0
13 to 13.9	2	0.74	0	0

Figure 6. Predicted (corrected) noise level error as function of several variables.





linear fit line lies very close to zero error for all variables.

The average error per location, after corrections were applied, was 1.9 dBA. This represents a 60 percent reduction in error from the uncorrected predictions. This error reduction is significant at the 0.01 level. After correction, the residual error between measured and corrected values was found not to be statistically significant at the 0.1 level, but significant at the 0.2 level. This remaining error might have been due to factors such as imperfections in data collection. The meter for measuring noise level was calibrated each day before recordings were made, and the strip-chart recorder was continually compared with the sound-level meter to ensure accurate readings, but some degree of error might be expected. Variable pavement types can cause variations in sound levels, and the adjustment for pavement type is probably inadequate since it simply provides for an adjustment of +5 dBA for rough pavements or -5 dBA for smooth pavements. In addition, types of cars and trucks that pass during recording periods vary. For example, the prediction procedure cannot provide for the percentage of tractor-trailers that pass. For a particular location and a given truck volume, the noise level will increase markedly as the percentage of tractor-trailers increases. The prediction procedure also does not account for differences in noise levels of a particular type of vehicle. Therefore, if an abnormal number of quiet or loud vehicles pass while the recording is being made, the measured noise level will differ from the predicted noise level.

Table 1 gives the distribution of differences between predicted and measured noise levels before and after corrections were applied. The number of locations with large errors was greatly reduced when the predicted noise level was corrected.

A statistical test was performed to evaluate the variability that remained after corrections were applied. Results indicated that error variability before correction was significantly larger than error variability after correction to the 0.01 level of significance.

CONCLUSIONS

1. A significant discrepancy was found between predicted and measured noise levels; the average error was 4.8 dBA.
2. A nomograph developed for the correction of predicted noise levels resulted in a significant reduction in errors. Significant corrections were necessary for (a) short observer-roadway distance and low truck volume (correction = 3 to 10 dBA, depending on average car speed), (b) short observer-roadway distance and low mean car speed (correction = 5 to 10 dBA, depending on truck volume), and (c) short observer-roadway distance, low truck volume, and low mean speed of the car (correction $\approx$ 10 dBA).
3. Although errors were substantially reduced, remaining errors (average of 1.9 dBA) indicate that further study of other variables should be made. In particular, more accurate adjustments are necessary for various pavement types. Variations of noise levels emitted from different vehicles cause error between predicted and measured noise levels, and further adjustments may be forthcoming.

IMPLEMENTATION

Approval to use the nomograph in Kentucky's noise prediction procedures was received from the Federal Highway Administration effective October 10, 1974. The nomograph has been incorporated into the computer noise prediction model and is now in use.

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SOCIOECONOMIC FACTORS AS DETERMINANTS OF NOISE ACCEPTANCE

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Among the many factors that influence residents living adjacent to a major transportation facility is noise. Since the ultimate criteria of public acceptance are based on annoyance levels rather than absolute noise levels, an investigation was undertaken concerning the relationship between annoyance and socioeconomic characteristics, such as social status, length of residence, and age, in primarily single-residence neighborhoods. Criteria for selection of the study areas were variation of neighborhood age, homogeneity, property values, proximity to a noise-generating transportation system, and freedom from other major noise generators, such as airport flight patterns. Although traffic volumes ranged from 84,000 to 52,000 average daily traffic, the noise levels were fairly similar in the study areas. The current assessed value of each improved residential property abutting the highway was obtained from the property tax assessors of Jefferson and Denver counties in Colorado. A total of 110 residences were sampled from a total population of 170 to determine the quantity and characteristics of highway noise annoyance. The results of this investigation show that socioeconomic variables explain only 5.6 percent of the variance in annoyance and that further investigation is not warranted.

•AMONG the many factors that influence residents living adjacent to a major transportation facility is noise. The effects of noise include interference with leisure, sleep, or conversation; decreased efficiency in both physical and mental tasks; fatigue; and potential or actual hearing loss.

Today, transportation planners are considering measures for noise abatement in planned projects as well as in existing problem corridors. The current popular evaluation technique involves field measurement of existing ambient noise levels and extrapolation to present or future design levels based on design traffic characteristics. Federal guidelines establish threshold levels above which some corrective measures should be taken.

Since the ultimate criteria of public acceptance are based on annoyance levels rather than on absolute noise levels, an important tool that could be used by transportation planners would be a guideline for determining the sensitivity of neighborhoods to noise generated by transportation systems.

This study proposes to evaluate the annoyance levels in single-residence neighborhoods displaying various socioeconomic characteristics where a similar noise environment exists and to determine the correlation between annoyance levels and certain socioeconomic characteristics.

PREVIOUS RESEARCH

Before the project goals were defined, an extensive review was undertaken of all available research material at the University of Colorado libraries, Denver Public Library, Colorado Department of Highways, and the noise office of the city of Lakewood. Because of the extensive research related to quantifying noise and attenuation techniques, annoyance due to transportation noise was investigated.

Hawel (1) discussed parameters for annoyance. The primary parameters discussed were situation, personality, activity, quality of sound, and noise level. Situation was examined relative to work, recreation, and sleeping; personality to humor; and activity to relaxing, arithmetic problems, and composition. Types of noise investigated ranged from traffic and construction noise to voices and music.

Kryter (2) discussed psychological techniques for reduction of annoyance levels and defined various techniques for evaluating certain components of noise to determine annoyance.

A study (3) of noise problems prepared before the Bay Area Rapid Transit System was constructed recommended that the cultural, economic, and leadership character of wayside communities be surveyed to determine the likelihood of complaints and possible legal action so that particular attention could be paid to noise control in sensitive areas.

As a result of these and other readings, it was decided that an investigation into the relationship between socioeconomic characteristics and levels of highway noise annoyance was warranted for possible use as a planning tool to be used by transportation planners and others concerned with noise abatement.

The following definitions are used in our paper:

dBA = single number rating read directly from the A scale of a sound-level meter that has electronic filters that approximate the human ear's response to different frequencies; the rating has a high correlation with nearly steady-state wide-band, non-information-carrying noise, such as traffic noise (4);

L_{10} = noise level (dBA) that is exceeded 10 percent of the time;

L_{50} = noise level (dBA) that is exceeded 50 percent of the time; and

ambient noise = all-encompassing noise that is a composite of sounds from many sources at varying distance.

STUDY DESIGN

Selecting Study Areas

After the initial objectives had been established, the initial phase of the project was to select study areas. Criteria for selection of the study areas were variation of neighborhood age, homogeneity, property values, proximity to a noise-generating transportation system, and freedom from other major noise generators, such as airport flight patterns.

The primary study area was US-6 between Federal and Kipling Boulevards, a 4.5-mile (7.2-km) section of divided six-lane highway with average daily traffic (ADT) varying between 82,000 and 52,000 vehicles per day. Values of homes abutting US-6 range from less than \$10,000 to more than \$60,000. Some of the homes lie in relatively new subdivisions, less than 10 years old, and others are located on lots in excess of 1 acre (0.4 hm^2) with horses and other similar rural amenities. Some of the older subdivisions have been established for 50 years.

A secondary study area, located along I-25, contains a new (less than 10 years) and homogeneous neighborhood of upper middle class homes. These homes abut the four-lane divided highway, which is currently planned to be expanded to six lanes. The ADT along this section of highway is 84,000 vehicles per day. Most of these homes have low fences, are set back further from the highway than most homes in the primary study area, and have a mean value of \$50,000.

Determining Noise Levels

The process used to determine noise levels for the study areas began with field measurements of approximately sixty readings (dBA) at 5-sec intervals and simultaneous automobile and truck counts. The number of occurrences at each dBA level and of the measurement intervals, the distance from the center of the near lane, the percentage of the highway grade, the height above the highway at which the measurements were taken, the automobile and truck counts, the posted speed, and the design (current peak-hour) automobile and truck volumes were compiled. For the purpose of the study, 1972 Colorado Department of Highways traffic data were updated to the current year.

The Colorado Department of Highways computer program NODATA was used to compute L_{50} and L_{10} noise levels at the time of measurement and to extrapolate noise levels to design operation. In addition, the accuracy of each set of readings was computed. This method was used to standardize all noise data to be compatible with any other highway data. Although traffic volumes ranged from 84,000 to 52,000 ADT, the noise levels were fairly similar in the study areas.

Noise levels at 50 ft (15.2 m) from the near lane were determined for each of five sections in the primary study area and the supplementary study area where traffic volumes were the same. Noise levels (L_{10}, dBA) were then established for each residence by scaling aerial photos for the distance from the centerline to the near edge of each residence and by computing attenuation due to distance by $-20 \times \log$ (distance/50) (5). Although characteristics of terrain and vegetation varied, we thought that these factors would not greatly affect the final results of the study.

Determining Annoyance

We wanted to interview as many residents as possible whose houses abutted the highway. Multiunit dwellings were avoided since it was thought that apartment residents would be more compromising in their noise acceptance than those living in single residences. However, seven duplex residences were surveyed because they were part of largely single-residence neighborhoods. A total of 110 residences were sampled from a total population of 170.

In series 1, the following questions were asked of each person surveyed:

1. Given the categories of very high, high, disturbing, or no concern, how would you rate your concern about air pollution as it affects you?
2. Given the same categories, how would you rate your concern about water pollution as it affects you?
3. Given the same categories, how would you rate your concern about noise levels, as they affect you?

The ratings for each response are given in Table 1. The purpose of the indirect lead-in was to avoid immediate bias against highway noise, since it has been shown that early direct questioning on noise tends to bias the level of annoyance (6).

The question in series 2 was, What source of noise bothers you most: people, machinery, aircraft, or surface transportation? The ratings of responses are given in Table 1. The particular sources for the responses were determined as follows:

1. People—shouting, radio, T.V., children, dogs, or playgrounds;
2. Machinery—lawn mowers, chain saws, or construction equipment; and
3. Surface transportation—cars, trucks, motorcycles, buses, or trains.

Trains was never given as a response.

Series 3 determined whether the noise bothered the respondent at home by the following questions:

1. Where does noise bother you most: home, work, commuting, or recreation?
2. Does noise bother you more indoors or outdoors?
3. Does noise bother you more while you are sleeping or working?

Questions 2 and 3 were asked when the response to question 1 was home. The values assigned to each response are given in Table 1. The weighting of the responses from question 1 in series 3 was designed to place more emphasis on the responses of those whose source of annoyance was the highway and to give minor consideration to those whose annoyances were transportation oriented. The values attached to question 2 were used to give additional consideration to those whose noise problems stemmed from areas where levels were lower because of the significant attenuation inside a dwelling. Similarly, for question 3, sleeping was given more consideration than working because a person is apt to be more sensitive when sleeping.

The questions in series 4 were as follows:

1. When does noise bother you most: summer or winter?
2. Is there a particular time of day when noise bothers you more: morning, afternoon, or evening?

These questions were weighted as given in Table 1. Winter was weighted heavier because traffic volumes are lower and people are less likely to be outside. The time of day variables were given arbitrary assignments.

The questions in series 5 were as follows:

1. Do you think that there is adequate noise control legislation?
2. Would you consider joining an organization whose purpose is to have noise levels reduced?

Question 2 was asked if no was the answer to question 1. Questions in series 5 were designed to verify and strengthen the annoyance level determined from the previous responses. The responses were weighted as given in Table 1.

In series 6, there was a single noise-related question: Do you think that noise has increased over the past 5 years? The weighting of responses is given in Table 1. The purpose of this question was to determine residents' awareness of the noise around them.

The following demographic questions were then asked:

1. How long have you lived in this area?
2. What is your occupation?

The occupation categories (not including the unemployed category) are given in Table 4. The following information was determined at the time of interview by the interviewer:

1. Date;
2. Time;
3. Address;
4. Age of respondent;
5. Weather—rainy, cloudy, sunny;
6. Temperature—cool, mild, hot;
7. Interview situation—indoors or outdoors; and
8. Noise at the time of interview—quiet, moderate, or loud.

Determining Property Values

The current assessed value of each improved residential property abutting the highway was obtained from the property tax assessors of Jefferson and Denver counties in Colorado. A recent study by the Colorado Property Tax Division determined that property was currently being assessed at a rate of 13.9 percent in Jefferson County and 23.1 percent in Denver County. Assessed values were adjusted accordingly. Neighborhood groupings were then made by natural breaks (major streets, changes in land use, or major changes in residential character). Mean property values and standard deviations were computed for each parcel abutting the highway in each neighborhood.

Property values for the entire neighborhood were not considered since property values for residential parcels abutting the highway were shown to be substantially lower where noise is a problem (7).

Figures 1, 2, 3, 4, and 5 show locations where noise measurements were taken $\boxed{\triangledown}$ and the corridor along the highway where peak noise levels exceed the current Federal Highway Administration standards (8, 70 dBA, outside residential areas) ≈≈≈≈. Homes interviewed in this survey are shown by ◆. Because the primary study area is being considered for possible noise abatement by the Colorado Department of Highways, FHWA is currently undertaking a similar survey. Homes interviewed in the FHWA survey are shown by ◇. The scale on these figures is approximately 1 in. (2.5 cm) equals 700 ft (213 m).

RESULTS AND STATISTICAL ANALYSIS

Variables Analyzed

The following variables were used in this study:

CONAIR = response to concern about air pollution,
CONWATER = response to concern about water pollution,
CONNOISE = response to concern about noise levels,
SOURCE1 = basic noise source (e.g., surface transportation),
SOURCE2 = specific noise source (e.g., trucks),
WHERE1 = where, specifically, noise is a problem (e.g., home),
WHERE2 = where, generally, noise is a problem (indoors or outdoors),
WHERE3 = where activity is when noise problem is greatest,
WHEN1 = time of year when noise problem is greatest,
WHEN2 = time of day when noise problem is greatest,
LEGCOCN = response to question regarding adequate noise control legislation,
LGCOCN2 = response to question regarding joining a noise control organization,
AWARE = awareness of noise increase,
LENGTH = length of residence in years (or fraction thereof),
AGE = age of respondent,
OCCUP = occupation,
TIME = time of day of interview,
ENV1 = temperature,
ENV2 = weather,
ENV3 = indoor or outdoor interview,
ENV4 = noise at interview,
MVAL = market value of property,
RESTYPE = single or multiple unit,
MEANVAL = mean market value of neighborhood properties abutting highway,
STDEV = standard deviation of neighborhood properties,
IMPRATIO = ratio of assessed value of improvements to assessed value of land,
RESFCTR1 = MVAL - MEANVAL,
RESFCTR2 = MVAL - MEANVAL/STDEV,
ANNOY = composite annoyance,
DISTFCTR = distance from the center of downtown Denver to each house,
DIST = distance from the center of highway to near edge of dwelling,
NOISELV = noise level computed to the near edge of house by means of DIST,
L_{10} = L_{10} noise levels at 50 ft (15.2 m) from near lane, and
L_{50} = L_{50} noise levels at 50 ft (15.2 m) from near lane.

IMPRATIO, RESFCTR1, and RESFCTR2 were used to evaluate the relationship between individual property and neighborhood property values.

Table 1. Responses to questions and ratings.

Series	Question	Response	Rating
1	1, 2, 3	No concern	0
		Disturbing	1
		High	2
		Very high	3
2	1	People	1
		Machinery	1
		Surface transportation	5
		None	0[a]
		All	2[b], 4[c]
3	1	None	0
		Recreation	1
		Work	1
		Commuting	2
		All	3
		Home	5
	2	Outdoors	2
		All	3
		Indoors	4
	3	Working	2
		All	3
		Sleeping	4
4	1	None	0
		Summer	1
		All	2
		Winter	3
	2	None	0
		Morning	1
		Afternoon	2
		Evening	3
		All	4
		Multiple	5
5	1	Yes	1
		Uncertain	2
		No	3
	2	No	1
		Uncertain	2
		Yes	5
6	1	No	0
		Uncertain	1
		Yes	3

[a]Also for other than transportation-related sources. [b]Single response. [c]Multiple response.

Figure 1. Sixth Avenue, Kipling Street to Carr Street.

Figure 2. Sixth Avenue, Carr Street to Otis Street.

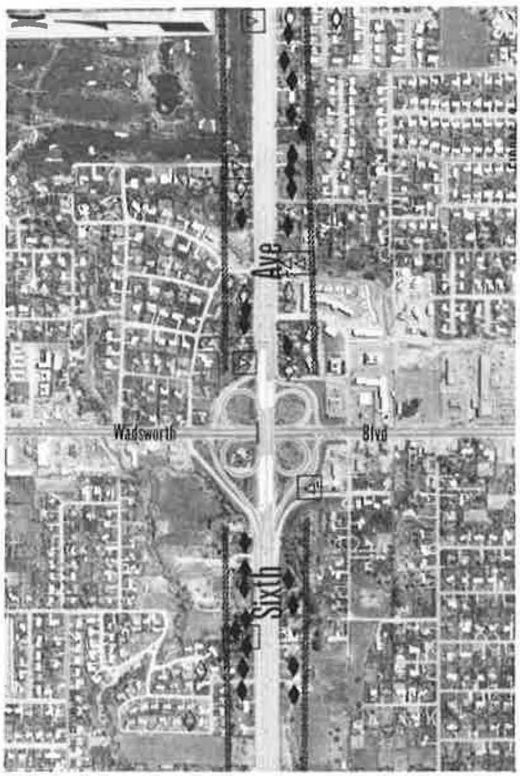

Figure 3. Sixth Avenue, Otis Street to Xavier Street.

Figure 4. Sixth Avenue, Xavier Street to Knox Court.

Figure 5. I-25, Hampden Boulevard south.

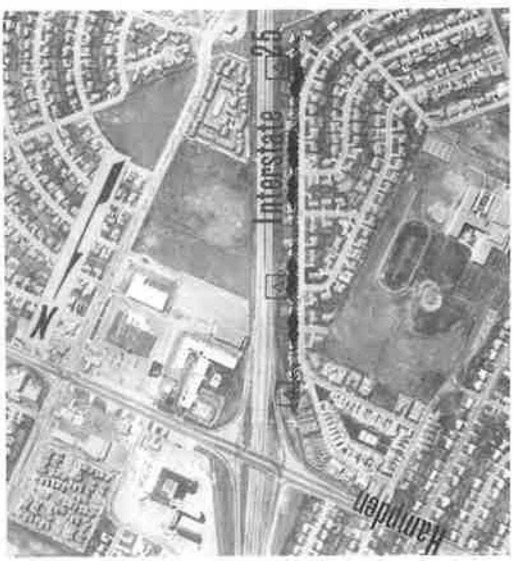

Table 2. Correlation values above 0.50.

Correlation	Value	Correlation	Value
NOISELV with DIST	0.77[a]	MEANVAL with DISTFCTR	0.80[c]
MVAL with MEANVAL	0.82[b]	MVAL with DISTFCTR	0.70[c]
MVAL with RESFCTR1	0.54[b]	LENGTH with AGE	0.52[d]
MVAL with RESFCTR2	0.52[b]		

[a]Expected since noise level is computed nonlinearly from distance.
[b]Not significant since all these variables are constructed from MVAL.
[c]Peculiar, although probably typical relationship between property values and distance from CBD of a city the size of Denver.
[d]Not surprising since length of residence depends on person's age.

Composite Variable of Annoyance

Since there are several questions relating to annoyance, a single variable representing annoyance was to be developed. The following variables were thought to be most significant in their association with annoyance: CONNOISE, WHERE1, SOURCE1, LEGCOCN, and LGCOCN2. CONNOISE, representing the general noise concern, was used as a key variable, and WHERE1 and SOURCE1 were used as multipliers to define and weight the annoyance as highway-related annoyance at the respondent's home. The questions regarding adequate legislation and possible joining of a noise control organization (LEGCOCN and LGCOCN2) were handled separately and added to the previously computed value, as shown below:

$$\text{ANNOY} = \text{CONNOISE} \times (\text{SOURCE1} + \text{WHERE1}) + \text{LEGCOCN} \times \text{LGCOCN2} \tag{1}$$

For example, if a person was very concerned about noise levels (CONNOISE = 3), indicated the highway as the source of the noise (SOURCE1 = 5), was most disturbed at home (WHERE1 = 5), thought there was inadequate noise control legislation, and was even willing to join a noise control group (LEGCOCN = 3; LGCOCN2 = 5), the person would be given a maximum score of 45. On the other hand, if the source of noise is other than the highway or if the noise problem is greater in a location other than the home, the annoyance level would be substantially lower. The possibility of a particularly noisy place of employment was examined by the subprogram CROSSTABS that compared occupation with WHERE1.

Variable Correlation

The first part of the analysis phase was to compute means and standard deviations for each of the variables and a correlation matrix by the statistical package for the social sciences (SPSS) on the University of Colorado's computer. All correlations above 0.50 are given in Table 2. There is an extremely low correlation between ANNOY and the socioeconomic variables (Table 3). The best correlation, although very poor, is CONAIR. Since annoyance is a composite of the variables related to the annoyance questions, they were not included in Table 3.

Sample Distribution

As a check for biased sampling, Table 4 gives frequencies of certain characteristics of the respondents. Age, length of resistance, and market value are well distributed. On the other hand, occupation has only light representation in factory, sales, labor, and self-employed categories, and housewives dominate the occupation frequency (39.1 percent). However, the survey represents 65 percent of the total households abutting the freeway. Table 4 also indicates that most of those surveyed live within a similar proximity of the highway and that 93.6 percent live in single-residence dwellings. Table 5 shows the absolute and relative frequencies for ANNOY; they demonstrate a great deal of variance.

A factor analysis was performed so that a better correlation matrix could be developed. This, however, did not significantly affect the relationship between socioeconomic variables and annoyance variables. Further occupation data were stratified by distance from the highway, and a cross-classification analysis was performed. Again no significant relationship was developed.

Table 3. Correlation coefficients of composite annoyance variable related to other socioeconomic variables.

Variable	Value	Variable	Value
DIST	0.13785	MEANVAL	0.13362
NOISELV	0.09457	ENV1	0.15145
DISTFCTR	0.04312	ENV2	0.02399
MVAL	0.11117	ENV3	-0.14134
RESFCTR1	-0.00171	ENV4	-0.01834
RESFCTR2	0.02016	TIME	-0.09280
IMPRATIO	0.14123	CONAIR	0.44375
AGE	-0.00928	CONWATER	0.02065
LENGTH	-0.03965	AWARE	-0.15345
RESTYPE	0.21328		

Table 4. Frequency distributions of certain characteristics of respondents.

Item	Description	Relative Frequency (percent)
Age, years	<20	7.3
	20 to 29	18.2
	30 to 39	20.9
	40 to 49	24.6
	50 to 65	14.5
	>65	14.5
Occupation	Professional	15.2
	Office	5.5
	Sales	1.8
	Self-employed	3.6
	Laborer	4.5
	Factory	2.7
	Housewife	39.1
	Retired	15.5
	Student	11.8
Type of residence	Duplex	6.4
	Single	93.6
Length of residence, years	<1	12.7
	1 to 5	32.8
	6 to 10	14.5
	11 to 15	13.6
	16 to 20	9.1
	21 to 25	5.5
	>26	11.8
Market value of property, dollars	<10,000	3.6
	10,000 to 19,999	20.0
	20,000 to 29,999	22.8
	30,000 to 39,999	22.7
	40,000 to 49,999	20.0
	50,000 to 59,999	8.2
	>60,000	2.7
Distance from center of highway, ft	<100	20.0
	100 to 200	74.5
	200 to 300	5.5

Note: 1 ft = 0.3 m.

Table 5. Computed frequencies for composite annoyance variable.

Value	Absolute Frequency	Relative Frequency (percent)	Value	Absolute Frequency	Relative Frequency (percent)
1	3	2.7	22	4	3.6
2	7	6.4	23	2	1.8
4	4	3.6	24	4	3.6
5	1	0.9	25	5	4.5
6	1	0.9	27	1	0.9
7	1	0.9	28	1	0.9
9	2	1.8	30	1	0.9
10	4	3.6	31	1	0.9
11	3	2.7	32	4	3.6
12	1	0.9	33	11	10.0
13	2	1.8	34	2	1.8
14	7	6.4	35	3	2.7
15	1	0.9	36	7	6.4
16	2	1.8	45	20	18.2
17	2	1.8	Total	110	100.0
21	3	2.7			

Table 6. Multiple regression summary for composite annoyance as dependent variable.

		F to Enter						Overall F	
Step	Variable Entered	Value	Significance	Multiple R	R^2	R^2 Change	Simple R	Value	Significance
1	RESTYPE	5.15	0.025	0.21	0.05	0.05	0.21	5.15	0.025
2	NOISELV	3.85	0.052	0.28	0.08	0.03	-0.20	4.57	0.012
3	MVAL	0.52	0.473	0.29	0.08	0.00	0.10	3.20	0.026
4	DISTFCTR	0.59	0.444	0.30	0.09	0.01	0.04	2.54	0.044
5	AGE	0.20	0.658	0.30	0.09	0.00	-0.02	2.06	0.077
6	IMPRATIO	0.17	0.680	0.30	0.09	0.00	0.14	1.73	0.122
7	RESFCTR2	0.11	0.743	0.30	0.09	0.00	0.02	1.48	0.181

Multiple Regression Analysis

The final analysis subprogram used was REGRESSION, in which a stepwise multiple regression was performed. The dependent variable used was ANNOY. As given in Table 6, these socioeconomic variables only explain 5.6 percent of the variance of ANNOY.

So that the possibility of poor construction of the annoyance variable ANNOY could be considered, a similar regression analysis was performed by using all of the annoyance variables as independent variables and MVAL as the dependent variable. The results indicate that little of the variance of the variable MVAL can be explained by the annoyance variables. No significant relationship between the socioeconomic characteristics investigated and the annoyance factors was discovered.

CONCLUSIONS AND RECOMMENDATIONS

Unquantifiable Results

Two respondents thought that the construction of I-70, a parallel route to US-6, had removed a great deal of truck traffic. If some truck traffic has been diverted, it has nevertheless continued to increase along US-6. Annoyance levels for these two respondents were lower, and this agreed with the idea that annoyance levels are closely associated with psychological attitudes (9).

Many of the interviews that were conducted in extremely high noise levels resulted in rather low annoyance levels. Before the data analysis phase, a strong relationship between low annoyance levels and length of residence was expected because these people had gradually become accustomed to their noise environment. However, a significant fraction of the long-term residents are actively involved in a citizens' group attempting to have noise levels reduced. Therefore, length of residence can result in a gradual conditioned response to noise; it also can increase annoyance for those who feel that their activities are increasingly being interrupted by noise. Thus, length of residence, like other socioeconomic characteristics, can play either a positive or negative role in the determination of annoyance.

Other Considerations

A final, single direct question regarding the specific annoyance of the highway at home might have been helpful to verify the composite annoyance variable. However, it is not expected that this would have had a significant effect on the results of this study. Since evidence is increasing that noise increases susceptibility to emotional problems and loss of sleep, which results in increased irritability and tension (10), indirect questioning might have been considered for indicators of personal stress to give minor consideration to psychological factors.

As given in Table 5, the socioeconomic characteristics are well distributed. The types of neighborhoods sampled ranged from those with homogeneous track homes to those with long-established homes on large lots. The survey investigated all major types of single-residence neighborhoods, and as such is a valid representative sample. The composite variable ANNOY was also well distributed, and this provided an opportunity for developing a correlation to related factors.

Through a larger sample, a better relationship between annoyance and socioeconomic variables might be developed. However, a major improvement in the 5 percent explanation of variance would still not result in a significant relationship. Because of this, further analysis and investigation does not appear to be warranted.

ACKNOWLEDGMENTS

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EVALUATION OF AIR AND NOISE POLLUTION IMPACTS DURING THE HIGHWAY SYSTEM PLANNING STAGE

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The Pennsylvania Department of Transportation, in response to an increasing interest in the protection of the quality of the human environment, has undertaken the evaluation of environmental impacts during the highway system planning stage. This paper considers air and noise pollutants. The relationship between system planning and project planning is discussed, a framework for analysis is presented, and types of studies conducted by the system planning staff are defined. A macroscale study estimates the impact of an entire highway system on air quality and traffic noise levels in an urban area. A mesoscale study estimates the impact of an individual project on air quality in an urban area. Data needed to effectively evaluate air and noise pollution impacts at the system planning stage are discussed. Types of air quality models and their limitations and application to macroscale and mesoscale studies are considered. A highway noise model and its adaptation to system planning requirements and strategies for abatement of air and noise impacts are discussed.

•THE purpose of this paper is to describe the technical procedures that the Pennsylvania Department of Transportation is following during the system planning stage to analyze the impacts of transportation systems and individual projects on air quality and noise pollution. Figure 1 shows the relationship among the various analyses and reports that are required for urban transportation study areas. The first report is the environmental overview statement (EOS), whose purpose is to define the current environment of an urban area or region. The EOS is used as a data base for future studies; input to it consists of economic, sociological, and cultural factors; growth patterns; air and water quality; noise; environmental hazards; and environmental resources.

Alternate transportation systems within an urban area are developed through analysis at the system planning stage. Input to this analysis includes the proposed transportation plan itself, community goals and objectives, policy decisions, and the data base from the EOS. The output is the level of economic, social, and environmental impacts of the proposed plan and secondary impacts such as increased population growth caused by increased accessibility. These impacts for various alternate plans are reported in an economic, social, and environmental (ESE) evaluation statement.

The project planning stage tests alternative transportation corridors and alignments. Output from this analysis are the economic, social, environmental, and secondary impacts of each alternate. The impacts are included in the project environmental impact statement (EIS), which identifies potential problems and benefits of each alternate. The ESE evaluation statement is used as input to the project EIS.

An important aspect of the analysis procedure is the relationship between the system and project planning stage. Figure 1 shows that a proposed project can be evaluated at the system planning level as well as at the project planning level. The system planning evaluation will permit the testing of alternatives to the project, such as improving public transit service, car pooling, or not building the project at all. This paper deals with an air and noise pollution analysis at the system planning stage. The procedures are intended to be used in conjunction with urban transportation planning techniques.

FRAMEWORK FOR ANALYSIS

There are three general guidelines for evaluating air and noise pollution impacts of transportation systems. First, the analysis should be receptor oriented. Although overall indications of the change of air or noise pollution in the region are important to obtain, the final determination of the acceptability of the system should be based on the impact of the system on individual receptors in the region. For example, air quality in the region may be generally improved at the expense of seriously degrading the air quality at one or more specific receptors. Such conditions must be clearly identified during the system planning stage. At the start of a study, a set of sensitive receptors should be identified in the region. These receptors can include schools, churches, hospitals, residential developments, and outdoor recreation areas. They may also be natural receptors such as breeding and nesting grounds and shorelines. Existing as well as proposed future land use should be considered. The set of receptors can serve as a benchmark for comparing alternative transportation plans.

Second, air pollution concentrations and noise levels from a proposed highway system should be compared with base year conditions and target year do-nothing conditions as well as with absolute standards [for noise (18); for air (22)]. Comparison with absolute standards will ensure that legal requirements are met. Comparison with base year existing conditions and target year do-nothing conditions will provide an estimate of the impact on receptors. Base year air pollution and noise levels can be measured or estimated by mathematical models. Target year air pollution and noise levels must be estimated by mathematical models.

Third, whenever changes are made to the transportation network, all economic, social, and environmental factors should be reevaluated. There is a law of ecology that states that everything is interconnected. This means that a small modification to one environmental system might result in significant changes in other environmental, social, or economic systems. For example, construction of a bypass to reduce central city pollution and congestion can induce more suburban growth and contribute further to center city decay and suburban sprawl that is costly in land and resource consumption. It might increase trip lengths and automobile dependency and might encroach on ecologically valuable space. System planning should be able to identify the secondary as well as primary impacts of the transportation system.

SCOPE OF ANALYSIS OF AIR AND NOISE POLLUTION IMPACTS

The system planning staff of the Pennsylvania Department of Transportation evaluates areawide air and noise pollution impacts of transportation systems during the system planning stage and air pollution impacts of individual projects during the project planning stage. The transportation system is composed of existing and proposed transportation facilities. A project is an individual highway facility or portion of a highway facility.

The type of study conducted during the system planning stage is known as a macroscale study. The purpose of a macroscale study is to evaluate the impact of an entire transportation system on a region. Input to the macroscale study consists of the data base from the EOS for the region, the transportation system plan, the community goals and objectives, and the policy decisions, as mentioned previously. The macroscale study does not emphasize the impacts of individual projects but considers the impact of the system as a whole. The macroscale study is used to test alternative highway and transit plans. Output from the macroscale study is used as input to the ESE evaluation statement.

During the project planning stage, a mesoscale air pollution analysis is performed, whose purpose is to determine the impact of the project on the region. Input to the mesoscale study is similar to that of macroscale. The project is analyzed in the context of the adopted transportation plan. Alternative corridors (including the alternative of not building the project at all) and policy decisions are tested, and their impact on air quality in the region is determined. Output from the mesoscale study along with the

ESE evaluation statement is used as input to the project EIS.

A third type of air and noise study used in the EIS is called a microscale study. The microscale study is performed after design alternatives are chosen. Its purpose is to determine the impact of the project within the project's immediate corridor.

AIR POLLUTION IMPACT ANALYSIS

Data Requirements and Availability

Five types of data are required to perform a macroscale and mesoscale air quality analysis: traffic data, land use, emission factors, meteorological data, and ambient air quality. Detailed highway design data are necessary only for the microscale study. Whenever any data item is unavailable it is best to assume the condition that will produce the highest air pollution emissions and concentrations.

Traffic Data

Traffic volume, average speed, and percentage of trucks are needed for each link of the highway network under analysis for each hour of the day. These values can be obtained by applying appropriate hourly factors to average daily values normally output from the traffic assignment process. The hourly factors are stratified by link class (e.g., freeway or arterial) and area type (e.g., CBD or rural). Capacity restraint techniques are used whenever possible in the traffic assignments because of the sensitivity of emissions to speed. The amount of traffic in the urban area that occurs on streets not on the network is also estimated.

Land Use Data

Land use data are required so that sensitive receptors can be chosen. Existing land use is determined from surveys normally performed for an urban transportation study; future land use is used to determine future sensitive receptors.

Emission Factors

Emission factors are computed for carbon monoxide, hydrocarbons, and oxides of nitrogen. Emission factors are expressed in units of grams per vehicle miles (kilometers) of travel and are a function of average speed, percentage of trucks, model year age distribution of vehicles, and expected performance of emission control devices. Average speed and percentage of trucks are obtained from the transportation network. Age distribution is obtained from vehicle registration data and is assumed to be constant in future years. Methods for computing emission factors are available in another report (10).

Meteorological Data

Meteorological data are used to characterize the transport and diffusion of pollutants. Meteorological parameters can be estimated for each urban area from records available from the National Climatic Center in Asheville, North Carolina. Most urban areas within Pennsylvania have some source of meteorological data (e.g., airport, U.S. Weather Service), for which the National Climatic Center keeps records.

The following raw data items are required to develop the basic meteorological parameters: wind direction, wind speed, surface temperature, cloud temperature, and morning vertical temperature profile. The first four items are usually recorded as hourly observations; the morning vertical temperature profile is used to estimate mixing depth. At least 5 years of observations are used. Summaries of wind direction, wind speed, stability class, and mixing depth are used to develop worst and most frequent meteorological conditions for the urban area under study.

Ambient Air Quality

Ambient air quality data are used for two main purposes:

1. To characterize existing air quality for use as a base for estimating future air quality, and
2. To calibrate mathematical air pollution diffusion models.

Ambient pollutant levels are the most difficult data to obtain. Within the larger urban areas of Pennsylvania (Philadelphia and Pittsburgh), some historical air quality data are available, and limited continuous sampling programs are underway. The available data in these areas must be supplemented with other sampling in most cases. Within other urban areas of Pennsylvania almost no ambient air quality data are available. The Pennsylvania Department of Environmental Resources is in the process of developing an extensive network of air-monitoring stations; however, several years are expected to elapse before the network is fully operational.

Air Quality Models

There are three types of models available for estimating air quality: emissions model, proportional or rollback model, and diffusion model. The model used in a particular urban area depends on availability of input data.

Emissions Model

Calculation of emissions of carbon monoxide, hydrocarbons, and oxides of nitrogen is required initially for all types of air quality studies. The summaries and graphs developed through use of the emission model can be used to indicate links in the highway network having high emissions. Output of emissions from individual links can be used as input to a diffusion model. It is important to note that emissions are expressed in units of mass of pollutants emitted (grams or kilograms) and are not directly comparable with air quality standards that are expressed as concentrations in units of mass per unit volume (grams per cubic meter) or parts per million.

The Pennsylvania DOT has developed a computer program to compute carbon monoxide, hydrocarbon, and nitrogen oxide emissions for each link of a highway network. This program is similar to the SAPOLLUT program developed by the Federal Highway Administration. Input to the program consists of the following:

1. Highway network,
2. Factors stratified by link class and area type to convert average daily traffic to hourly traffic volume for each hour of the day,
3. Factors stratified by link class and area type to convert average daily speed to average hourly speed for each hour of the day,
4. Percentage of trucks stratified by link class and area type for each hour of the day, and
5. Year for which pollutant emissions are to be calculated.

Emissions for a link are computed by multiplying the emission factor by the traffic volume and by the link length. Emissions for automobiles and trucks are computed separately and added together to obtain total link emissions. Output of the computer program consists of the following:

1. Magnetic tape containing total emissions of carbon monoxide, hydrocarbons, and oxides of nitrogen for each hour of the day for each link. This tape includes the X-Y coordinates of the endpoints of each link and can be used as input to an areawide diffusion model or used to make additional summaries not given below.
2. Listing of the emissions of each pollutant for each link for selected hour periods of the day. The worst hour of the day for emissions of each pollutant is indicated for each link. This listing can be used to determine links with high emissions.
3. Summary of emissions of each pollutant for selected hour periods cross-classified by link class and area type.
4. Listing of total emissions of each pollutant summarized by traffic analysis zone.
5. Total daily emissions of each pollutant for the entire network.

Figure 2 shows a typical graph that can be constructed from emissions output and that can be used to compare alternative networks. The two curves on the graph represent the range of emissions. The upper curve represents the maximum emissions and assumes that full growth will occur with no changes in the transportation network. The lower curve represents minimum emissions and assumes that no growth and no change will occur in the transportation network. The decrease of emissions from the base year for both curves is due to emission control devices on motor vehicles. The points on the graph represent emissions from alternative network configurations.

Rollback Model

A rollback or proportional model assumes that there is a direct linear relationship between pollutant emission and concentration. For example, if emissions of carbon monoxide are halved, the reference carbon monoxide concentration at a sampling site is also assumed to be halved. The rollback model is applicable only if ambient pollutant levels are available for use as reference concentrations. Concentrations from nonhighway sources of emissions must be added to those from highway sources. The major disadvantage of the rollback model is that the resultant concentration is assumed to be constant over a large area; it does not vary from receptor to receptor. The major advantages of the rollback model are that it is simple to apply (if ambient data are already available) and that it makes use of measured pollutant concentrations rather than simulated values. Computation of emissions is necessary before the rollback model can be applied.

The rollback model has three main uses. First it can be used to determine if ambient air quality standards will be exceeded in the future by a particular highway network. It is important to note that, even though the ambient concentration is not exceeded on an areawide basis, the concentration at individual receptors may be higher because of contributions from highways within their own corridors. The results of the rollback model, therefore, should be considered as a general guide in evaluating a highway network. Second, it can compare alternate highway network configurations. Since a direct relationship between concentration and emissions is assumed, the same results could be obtained by comparing emissions alone. Third, it can project base year ambient conditions to a future year and add them to the results of a line-source model for a particular highway. If used in this manner an additional assumption is that the ambient concentration is caused by emissions from all highways in the area except the highway under study. Within the highway, corridor concentrations estimated by a line-source model are added to the ambient concentrations predicted by the rollback model.

Diffusion Models

Diffusion models represent a higher level of sophistication in air quality modeling. A diffusion model is used to estimate the concentration of a pollutant at a receptor caused

Figure 1. Economic, social, and environmental impact analysis.

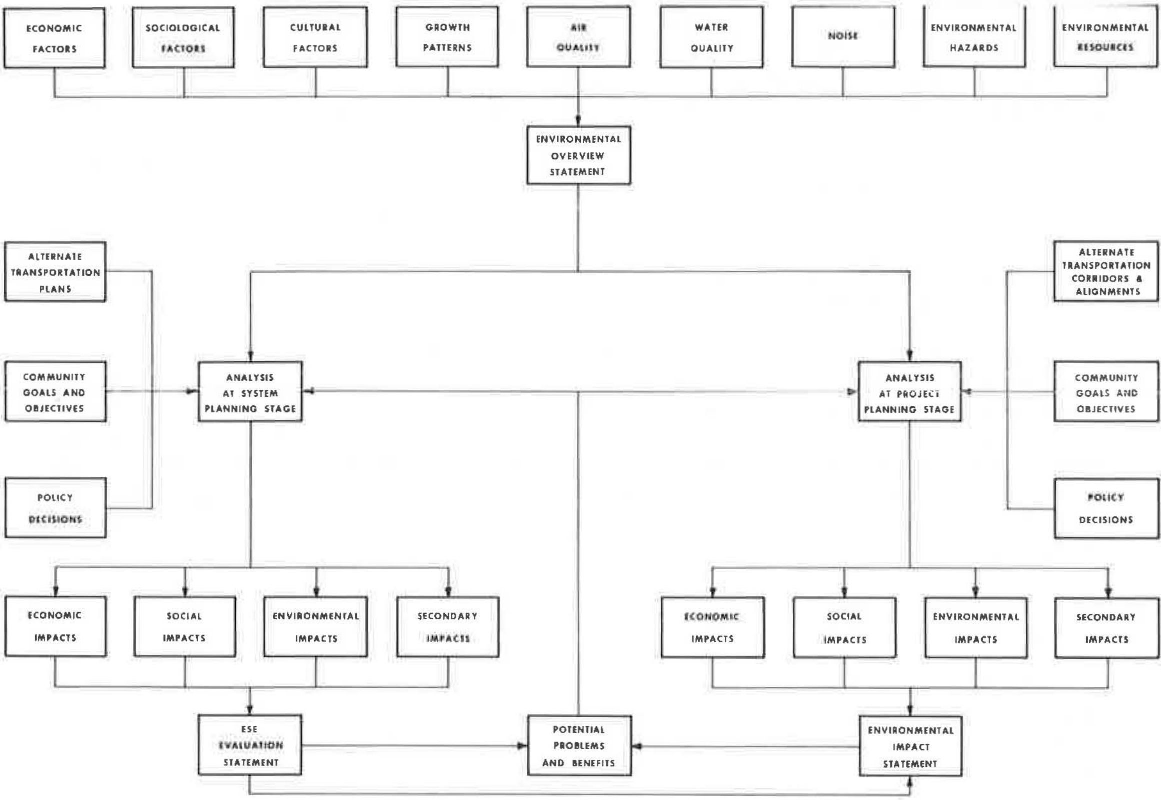
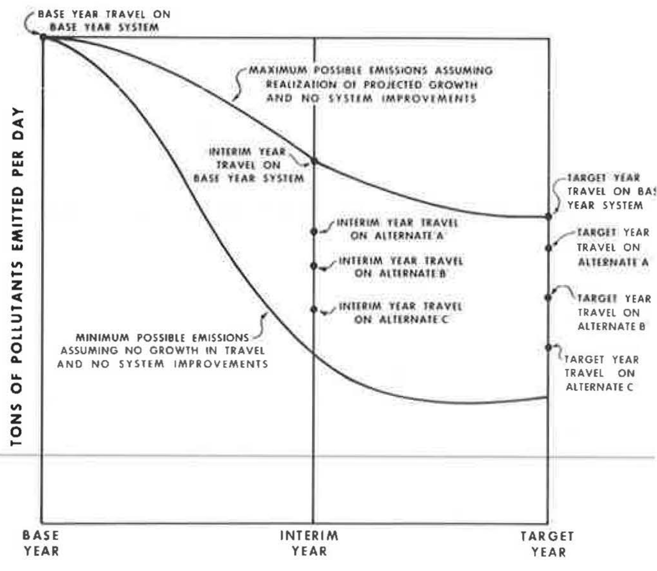


Figure 2. Comparison of alternative transportation systems based on annual variation of daily pollutant emissions.



by one or more sources. Input to a diffusion model generally consists of source emission rates, meteorological data, and the spatial relationship between sources and receptors.

The diffusion model adopted by Pennsylvania DOT for use in system planning is the APRAC-1A urban diffusion model developed by the Stanford Research Institute. This model can be used to estimate carbon monoxide concentrations only. The computer program for this model has been modified to directly accept output from the emissions model computer program. APRAC computes the concentration on carbon monoxide caused by emissions from the highway network at selected receptors in the urban area for selected hours of the day. Input to the APRAC model consists of the following:

1. Emissions model output, which includes the carbon monoxide emissions for each hour of the day for each link of the highway network and X-Y coordinates of the endpoints of each link;
2. Background carbon monoxide emissions, which account for emissions from traffic on streets not on the highway network and are usually assumed to be negligible;
3. X-Y coordinates of sensitive receptors in the urban area;
4. Average wind direction, wind speed, surface temperature, and cloud cover for each hour of the day; and
5. Morning vertical temperature profile.

Output consists of the carbon monoxide concentration at each receptor for selected hours of the day.

APRAC, as originally developed, is intended to be used in conjunction with the street canyon submodel to estimate carbon monoxide concentrations on downtown streets. Except for Philadelphia and Pittsburgh, no urban areas in Pennsylvania have street canyons as defined in the model. Pennsylvania DOT has been using APRAC without the street canyon submodel to estimate background concentrations in small urban areas. The background concentrations represent rooftop level, not street level, and are considerably lower than would be expected. Therefore, the department has been using APRAC as a guide to locate receptors having high concentrations. APRAC output is not compared with national ambient air quality standards.

Air Pollution Abatement Strategies

During system planning, there are numerous strategies and policies that can be tested. One important air pollution abatement measure is to increase transit ridership (19) by use of direct incentives, actions designed to increase high vehicle occupancy. These include

1. Use of public information program,
2. Improvement of transit system maintenance,
3. Improvement of transit customer service,
4. Encouragement of CBD businesses to provide voluntary rebate on transit fares for customers and employees,
5. Encouragement of CBD employers to stagger work hours,
6. Use of exclusive lanes for buses and high-occupancy vehicles,
7. Restructuring of bridge tolls to decrease cost for high-occupancy vehicles, and
8. Encouragement of car pools.

Automobile disincentives, measures that tend to discourage automobile use, can also be implemented to increase transit ridership. These include

1. On-street parking limits and cost increases for parking in private and commercial parking facilities, and
2. More effective enforcement of traffic and parking regulations.

Direct restraints, measures that prohibit or reduce vehicle use, can be implemented as well to increase transit ridership. These include

1. Prohibition of certain groups of vehicles from the CBD on given days,
2. Gasoline rationing,
3. Prohibition of vehicles from selected areas of the city, and
4. Monitoring of ramps to restrict vehicles entering freeways.

During location and design stages, the following measures can be taken to decrease air pollution concentrations due to a highway:

1. Design the facility to operate at a high level of service and thereby increase speeds and decrease emissions of carbon monoxide and hydrocarbons,
2. Purchase extra right-of-way where high concentrations are expected close to the highway,
3. Design the facility as an elevated section near sensitive receptors, and
4. Shift the highway location away from sensitive receptors.

Other methods of minimizing adverse effects of air pollution include

1. Requiring pre-1968 vehicles to be equipped with emission control devices,
2. Reevaluating land use plans to discourage sensitive receptors from locating near high-volume facilities,
3. Reducing or at least not increasing the density [highway miles (kilometers) per square mile (square kilometer) of land area] of the transportation network, and
4. Zoning.

The cost and technical and political feasibility to implement all recommendations should be computed and, if found to be reasonable, the system should be modified and tested. If the cost is not reasonable, new transportation plans and policies should be developed and tested to determine the impact on economic, social, and environmental systems.

NOISE POLLUTION IMPACT ANALYSIS

Data Requirements and Availability

The major items required for an impact analysis of noise pollution are traffic data, land use data, and ambient noise levels. The first two items are the same as those required for an air pollution impact analysis previously discussed. Ambient noise levels are used to estimate the impact of the highway system on a receptor. Table 1 gives some typical continuous background noise levels (dBA).

Highway Noise Model

The highway noise model adopted for use by Pennsylvania DOT is described elsewhere (14). The computer program has been modified to accept output from the traffic assignment process. Input to the noise model consists of the following for each receptor:

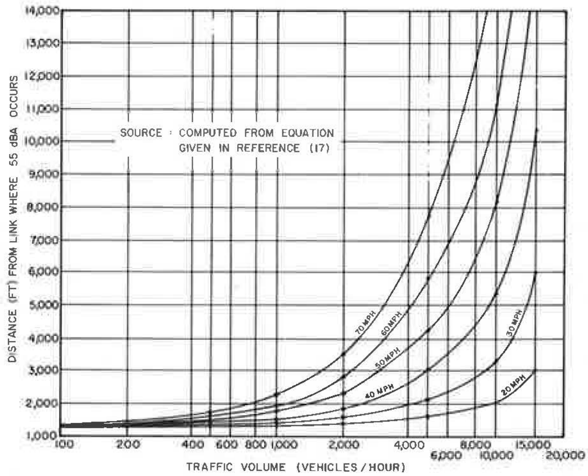
1. X-Y coordinates,
2. Ambient L_{10} and L_{50} noise levels,
3. Land use category, and
4. Building noise reduction (if interior noise standard applies).

Table 1. Typical continuous background noise levels.

Land Use	L_{10}	L_{50}
High-density residential	75	51
Medium-low-density residential	53	49
Industrial	60	55
Commercial	58	52
Central business district	73	67
Park and open space	51	46

Note: These data are based on readings taken during off-peak hours in York, Pennsylvania, where population in 1970 was 130,055.

Figure 3. Distances from highway link where 55 dBA occurs.



Output from the air pollutant emission program includes the following:

1. X-Y coordinates of the endpoints of each link,
2. Automobile and truck volumes for the hour period of interest,
3. Automobile and truck speeds,
4. Number of lanes,
5. Elevated or depressed height of link,
6. Percentage of grade,
7. Type of traffic (free or interrupted), and
8. Type of roadway surface (smooth, normal, or rough).

Outputs of the program are the L_{10} and L_{50} noise levels caused by the highway network. A program option permits comparison of the outputs with Federal Highway Administration standards (18) and with estimates of the impact of a proposed highway and the expected community response based on criteria in the NCHRP report (14).

To use the program, the analyst must determine which links contribute to the noise level at each receptor. All links that may contribute 55 dBA or more are included. Figure 3 shows the distance from the link where 55 dBA will occur as a function of traffic volume and speed. The program uses X-Y coordinates to determine the spatial relationship between the receptor and links, element type, and angle necessary for the model. In addition, it is possible to input noise barriers and other structures that reduce noise.

Another version of the model, incorporated in the air pollutant emission program, is used to estimate the noise level at specific distances [e.g., 100, 200, and 500 ft (30, 61, and 152 m)] from each link of the highway network. This information is listed by hour period, and hours of highest noise are indicated. This can be used to identify links having the potential to exceed standards. This version of the model assumes that every link is an at-grade infinitely long section with grades less than 2 percent, free-flow traffic conditions, normal roadway surface, and no barriers. The output noise level is caused by the single link, not a combination of several links.

Macroscale Noise Pollution Analysis

A macroscale noise pollution analysis is conducted to determine the impact of the entire highway network on noise levels in the region. The first step in the analysis is to identify noise-sensitive receptors in the urban area. These include hospitals, schools, churches, residential developments, and outdoor recreation areas as specified in PPM-90-2 (18). Identifying every receptor in the study area is not necessary, but including only those receptors near facilities that have the potential to exceed standards or those near proposed facilities and existing facilities that will experience significant changes in traffic volume is necessary. Figure 3 can be used to determine whether the links cause significant noise at a receptor. Links with the potential to exceed standards and the hours of the day when highway noise is highest can be identified by using the computer program previously described. Links experiencing significant changes in traffic volumes can be identified from traffic assignment output.

To estimate the level of impact requires that an estimate of the ambient noise levels be available at each receptor. Ambient levels can be obtained from generalized values as a function of land use, or field measurements can be taken. Pennsylvania DOT is currently using generalized values as a function of land use for systems level evaluation. The computer program is used to estimate the noise level at each receptor caused by contributing links. If land use is input, the program will compare the highway noise level with the absolute standards (22) and will estimate the level of impact and expected community response to the highway. The results of the analysis are summarized, and potential problems and benefits are identified. This information is used as feedback to develop new alternative transportation plans. The results of the macroscale noise study are used as an input to the ESE evaluation statement for the adopted transportation plan.

Noise Abatement Strategies

Measures to reduce highway noise levels can be taken during system planning and during location and design. During system planning an attempt can be made to change travel patterns and demand for highway travel so that the need for highway links or the traffic volume on links with high noise output can be reduced by, for example, providing the alternative of public transit. The network configuration can be modified to reduce total traffic or truck traffic near sensitive receptors.

The land use plan can be modified so that less noise-sensitive land uses are located near links with high noise output.

During location and design the following steps can be taken to reduce highway noise:

1. Use noise barriers near sensitive receptors,
2. Shift highway alignment,
3. Elevate or depress the highway near sensitive receptors, and
4. Purchase additional right-of-way so that high noise levels are confined within the right-of-way.

All noise abatement measures should be analyzed to determine their effect on other economic, social, and environmental factors.

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VEHICLE NOISE SURVEY IN KENTUCKY

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Individual noise measurements were obtained for 10,500 motor vehicles operating on Kentucky highways. The roadways were selected to represent various geometric and environmental conditions and posted speed limits. Percentages of automobiles and trucks exceeding a given noise level were determined. As expected, noise levels of trucks were significantly higher than those for automobiles, and larger trucks produced higher noise levels than smaller trucks. For any vehicle type, noise increased as speed limit increased.

•STUDIES in several major American and European cities have shown that, despite the noise produced by aircraft, surface traffic, including automobiles, buses, trucks, and motorcycles, is the predominant and most widespread source of noise. Traffic noise, although recognized in the past as a nuisance by those subjected to it, has reached such levels in some urban areas that it is considered a major pollutant of the environment. It has been shown (1) that noise levels in certain areas are increasing at the rate of 1 decibel (dB) per year, a result of increasing traffic flow. Increased traffic volumes and construction of high-speed highways within densely populated areas in particular have aroused public concern. The rural resident, as well, has been concerned about the disruptive effects to the environment as a result of the location of major highways nearby. Therefore, while satisfying the needs and demands for improved transportation facilities, the highway engineer must consider the consequences of added noise on the community in the design, location, and construction of highways.

Highway-generated traffic noise emanates primarily from vehicle engine exhausts and from tire-pavement interaction. Under normal operating conditions, an automobile generates as much noise from the tire-pavement interface as from engine exhaust. Large diesel trucks are much noisier than automobiles and, even with maximum muffling, would be expected to produce significantly higher noise levels than automobiles at the same running speed because of the larger contact area under the tires. Noise produced at the tire-pavement interface, in particular, depends on speed and varies with pavement texture. Coarse-textured pavements are noisier than fine-textured pavements. Very smooth, glassy, nonporous surfaces tend to generate air noises, squeal, and reflect sound. The noise level at a particular highway site depends on the traffic speed, distribution of vehicle types, traffic density, roadway characteristics (e.g., grade, intersections, elevated or depressed roadway), noise attenuation barriers such as trees and shrubs, and distance from the traffic stream.

Abatement and control of noise within an environment involves the direct control of noise emitted by individual vehicles, traffic routing, and highway design. The highway engineer is primarily concerned with the last two categories since some degree of control can be exerted. Limiting or controlling vehicular engine and exhaust noise, however, remains in the hands of vehicle designers and manufacturers and is subject to possible legislative control. Several states (2) have enacted legislation that sets limits on noise levels for motor vehicles. When Congress passed the Noise Control Act of 1972, the federal government took an active role in promulgating noise emission standards for motor vehicles.

A study was conducted by the Bureau of Highways, Kentucky Department of Transportation, to determine noise levels generated by individual automobiles and trucks operating on Kentucky highways. A total of 10,500 noise measurements were made on roadways representing various geometric and environmental conditions and posted speed limits, and percentages of each vehicle type exceeding a given noise level were calculated.

PROCEDURES

Individual automobile and truck noise levels were measured in dBA with a Bruel and Kjaer precision sound level meter (type 2203). All measurements were taken at a distance of 50 ft (15.2 m) from the center of the traffic lane and approximately 4 ft (1.2 m) above the roadbed. The data were recorded manually by the operator as a vehicle passed. Measurements were taken only when the noise emitted by a single vehicle could be clearly isolated or distinguished from the noise of the traffic stream. The operator and the meter were stationed on the same horizontal plane as the traffic lane, but locations were varied to represent different geometric conditions: level roadways, plus or minus grades, and straight or curved sections. Roadways were also selected on the basis of posted speed limits ranging from 35 to 70 mph (56 to 113 km/h). Vehicle speeds were not measured. Truck noise data (500 trucks) were obtained at locations with posted speed limits of 70 mph (113 km/h) to distinguish between various classes of trucks.

FINDINGS

The noise survey was conducted in 1972 and 1973 and involved 8,000 automobiles (including four-wheel pickup trucks) and 2,500 trucks (55 of which were analyzed by truck type), as given below. A few motorcycle noise measurements were also obtained. The speeds refer to the posted speed limit, not to the speed at which the vehicles were operating (1 mph = 1.6 km/h).

Speed (mph)	Automobiles	Trucks
70	2,000	1,250
60	2,000	665
50	1,000	335
45	1,000	100
35	2,000	150

Automobiles

Influence of speed on automobile-generated noise is clearly shown in Figure 1, which shows the percentage of automobiles at or below a certain noise level. The lowest reading was 60 dBA in a 35-mph (56-km/h) speed zone, and the highest was 90 dBA on a 70-mph (113-km/h) road. The median levels ranged between 67 and 77 dBA. On highways with the same speed limit, ranges in noise levels were rather small and may be indicative of uniform traffic speed.

Table 1 gives the percentage of automobiles that exceeded a given noise level. For example, in 35-mph (56-km/h) zones, only 0.4 percent of the automobiles had noise levels above 76 dBA, and 65 percent of the automobiles exceeded this level on 70-mph (113-km/h) roads.

Trucks

Noise emitted by trucks ranged between 64 and 102 dBA. The higher noise levels were associated with the higher posted speed limits, as shown in Figure 2. The median

Figure 1. Cumulative percentages of automobiles versus noise levels for roadways with various posted speed limits.

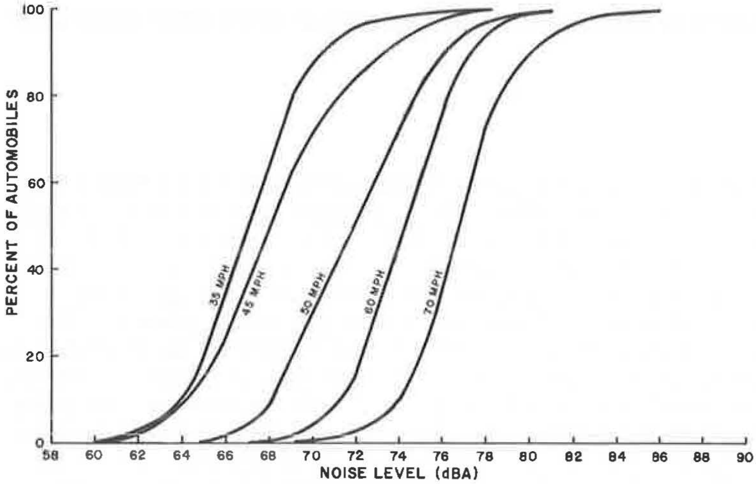

Table 1. Percentage of automobiles exceeding given noise level at various speeds.

Noise Level (dBA)	35 mph	45 mph	50 mph	60 mph	70 mph
90					0
89					0.1
88					0.2
87					0.3
86					0.2
85					0.3
84				0	0.6
83				0.1	1.6
82			0	0.2	2.9
81			0.4	0.6	5.2
80		0	0.8	1.4	9.9
79	0	0.1	1.3	2.7	17.7
78	0.1	0.2	2.2	5.2	27.2
77	0.2	0.7	5.7	11.6	45.4
76	0.4	1.5	9.8	22.0	65.1
75	0.7	2.9	19.2	37.4	79.2
74	1.1	7.1	26.9	55.0	92.2
73	2.3	12.6	37.9	73.8	96.8
72	3.7	15.9	46.9	85.3	98.4
71	6.4	21.8	57.7	93.8	99.0
70	12.2	28.1	69.8	96.6	99.4

Note: 1 mph = 1.6 km/h.

Table 2. Percentage of trucks exceeding given noise level at various speeds.

Noise Level (dBA)	35 mph	45 mph	50 mph	60 mph	70 mph
100				0.3	0
99				0.5	0.2
98				0.6	0.2
97				0.8	0.3
96			0	1.4	0.8
95			0.6	1.8	2.0
94			0.9	2.7	3.5
93	0		2.1	3.8	7.7
92	0.7		2.4	4.5	11.8
91	0.7		3.9	7.3	20.0
90	0.7		6.0	11.1	26.6
89	0.7	0	10.1	17.3	38.8
88	0.7	2.0	12.5	24.5	47.6
87	0.7	2.0	21.5	31.6	57.3
86	0.7	2.0	29.3	39.4	65.0
85	2.0	6.0	39.1	49.3	72.6
84	2.7	8.0	48.1	57.5	78.8
83	3.3	15.0	58.5	67.4	72.5
82	4.7	15.0	65.1	73.4	75.8
81	6.7	21.0	72.2	78.7	90.6
80	8.7	23.0	78.2	82.9	93.2

Note: 1 mph = 1.6 km/h.

Figure 2. Cumulative percentage of trucks versus noise levels for roadways with various posted speed limits.

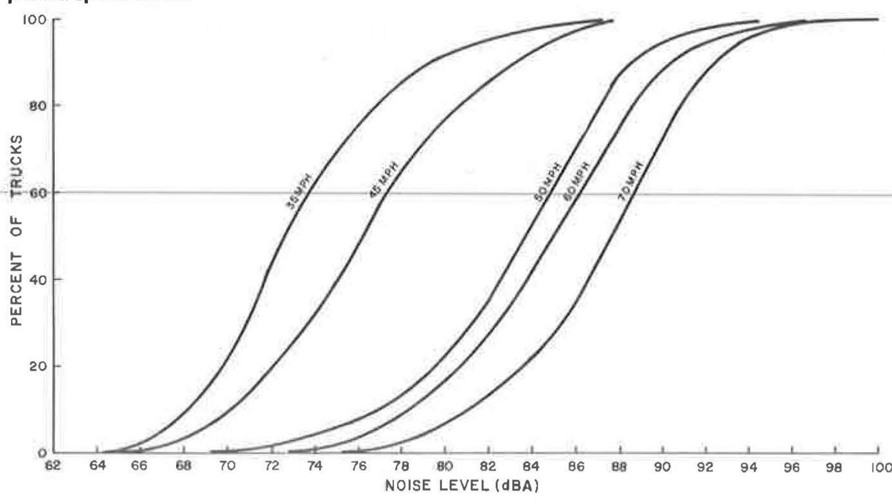

Figure 3. Cumulative percentage of trucks (by classification) versus noise levels for Interstate roads.

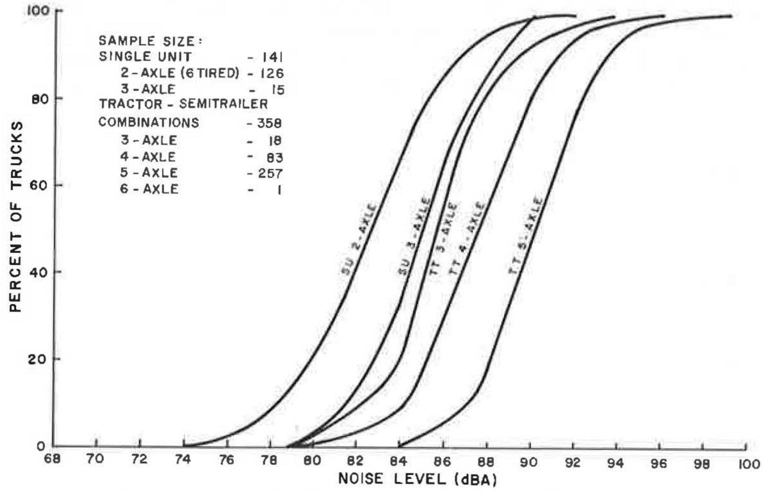

Table 3. Percentage of various truck types exceeding given noise level.

Noise Level (dBA)	SU Two-Axle[a]	SU Three-Axle[a]	TT Three-Axle[b]	TT Four-Axle[b]	TT Five-Axle[b]
100					0
99					0.4
98					0.8
97				0	1.2
96				1.2	1.6
95				1.2	3.5
94			0	2.4	6.2
93			5.6	3.6	14.0
92	0		5.6	6.0	22.6
91	0.8		5.6	14.5	35.8
90	0.8	0	5.6	19.3	48.2
89	3.2	13.3	11.1	33.8	69.3
88	4.8	13.3	16.7	43.4	81.3
87	6.3	20.0	27.8	61.4	87.5
86	12.7	33.3	44.4	69.9	94.6
85	27.0	46.7	72.2	77.2	98.8
84	38.1	66.7	83.3	91.2	100.0
83	46.8	73.3	83.3	96.4	100.0
82	54.0	86.7	88.9	97.6	100.0

[a]SU = single-unit truck. [b]TT = tractor-semitrailer truck.

noise level was 73 dBA in 35-mph (56-km/h) speed zones and 88 dBA on 70-mph (113-km/h) roads. Oddly, truck noise on roadways with posted 50 and 60-mph (80 and 97-km/h) speed limits exhibited a difference of only 1 dBA. Apparently the difference in average truck speeds was less than 10 mph (16 km/h). However, in the absence of corresponding data on vehicle speeds, statements regarding running speed, particularly in contrast to posted speed limits, may be inappropriate.

Percentage of trucks exceeding a given noise level is given in Table 2. Less than 1 percent of the trucks produced noise levels exceeding 86 dBA in 35-mph (56-km/h) speed zones. On roads with the high speed limits, 97 dBA was exceeded by less than 1 percent of the trucks operating under a 60-mph (97-km/h) speed limit. However, truck sizes determined generated noise levels; the larger trucks generated more noise. Figure 3 shows data for trucks operating on Interstate roads [70-mph (113-km/h) speed limit]. About half of the five-axle, tractor-semitrailer combination vehicles exceeded 90 dBA, but less than 1 percent of two-axle, single-unit trucks exceeded this level of noise. Table 3 gives the percentage of various classes of trucks that exceeded a given noise level on a 70-mph (113-km/h) road.

Motorcycles

No attempt was made in this study to collect a large sample of motorcycle noise data, but motorcycle noise levels were recorded at every opportunity. The following noise level readings were obtained (1 mph = 1.6 km/h). Even though the sample size was extremely small, the values may be indicative of noise levels peculiar to motorcycles.

Speed (mph)	Noise Level (dBA)
70	91, 89, 86
60	90, 83, 82, 82
50	79, 78
45	76
35	79, 76, 75, 72

SUMMARY AND DISCUSSION

Many automobiles and trucks were included in this study to obtain representative data on noise associated with moving motor vehicles. The survey was conducted on roadways representing various geometric and environmental conditions and posted speeds. The findings therefore reasonably reflect noise levels of vehicles operating on Kentucky highways.

As expected, noise levels of trucks were significantly higher than those of automobiles, and noise increased as the posted speed limit increased. The median vehicle noise levels (dBA) are given below (1 mph = 1.6 km/h):

Speed (mph)	Automobile	Truck
35	67	73
45	68	76
50	72	84
60	74	85
70	77	88

The lowest recorded reading was 60 dBA for automobiles in 35-mph (56-km/h) speed limit zones and the highest was 102 dBA for a single truck on a 60-mph (97-km/h) road. In addition, trucks consistently had a wider range in noise levels for a given speed limit than automobiles (Figure 1 and Figure 2). However, slopes of the cumulative percentage curves for individual truck types (Figure 3) were similar to those for automobiles (Figure 1). Noise levels of vehicles, therefore, were primarily related to vehicle size and speed. Data collected on motorcycles, even though limited, clearly indicated that motorcycle noise levels were comparable to those for trucks.

The purpose for this report was to give data and cite findings on vehicle noise rather than to recommend or suggest specific limits. The information, however, may be used as a guide in the consideration and establishment of noise standards to the extent that undue burden will not be placed on automobile or truck owners and operators or destroy commerce and travel in Kentucky. Therefore, the following suggestions and comments might be helpful:

1. Separate noise limits are warranted for automobiles and trucks because of the vast difference in noise generated by each vehicle type.

2. Noise emitted by vehicles depends on the operating speed. The higher noise levels were associated with the higher running speeds; therefore, separate limits should be set for vehicles operating in various speed-limit zones.

3. On roadways with posted speed limits greater than 35 mph (56 km/h), a single but higher noise limit may suffice. However, the practical consequences would be that the higher limit would largely affect those vehicle operators using Interstate and parkway roads with a posted speed limit of 70 mph (113 km/h). Perhaps a separate limit is warranted for 70-mph (113-km/h) roads and another limit for all roadways having posted speed limits between 40 and 60 mph (64 and 97 km/h).

ACKNOWLEDGMENT

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EVALUATION AND COMPARISON OF THREE AIR POLLUTION PREDICTION MODELS

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This paper presents a brief discussion of the theoretical and mathematical development of a line-source dispersion model AIRPOL-4 designed by the Virginia Highway and Transportation Research Council to eliminate some of the problems encountered with existing models. It also comparatively evaluates the predictive and cost performances of AIRPOL-4 with those of the California Division of Highways and the U.S. Environmental Protection Agency models. The predictive performances of these models are evaluated, against measured data, in relation to wind speed, road-wind angle, atmospheric stability class, source height, and receptor location. The results demonstrate that the predictive capability and reliability of AIRPOL-4 are generally superior to those of the other models. Comparison of cost performances for the models is based on operating costs determined for each of the models for air quality analyses involving identical input parameters. The results of this cost comparison demonstrate that AIRPOL-4 is significantly more cost effective than either of the other models.

MOTOR vehicles are a major source of carbon monoxide (CO) pollution. Consequently, CO concentrations are often highest in the vicinity of roadways. As detailed in the Federal Aid Program Manual, the Virginia Department of Highways and Transportation is required to estimate the impact of proposed highway facilities on the air quality in the region of such facilities. Currently, the CALAIR (1) and HIWAY (2) air pollution prediction models, developed by the California Division of Highways and the U.S. Environmental Protection Agency respectively, are the two prediction models generally accepted by the Federal Highway Administration for use in complying with the above requirements. These models are, however, cumbersome and expensive to use. They are, furthermore, generally inaccurate and tend to severely overpredict pollution levels in the critical cases of low wind speeds and small road-wind angles.

The Virginia Highway and Transportation Research Council has developed an air pollution prediction model, AIRPOL-4 (3), which is essentially free of the problems afflicting CALAIR and HIWAY. The purpose of this paper is to introduce AIRPOL-4 and to firmly establish, based on extensive field data, its utility and integrity. To accomplish this, the paper first presents the mathematical development of AIRPOL-4 and then analyzes and evaluates AIRPOL-4, CALAIR, and HIWAY on the bases of their cost performances relative to each other and their predictive performances relative to observed field data and to each other. The paper thus presents the development of AIRPOL-4 and determines both absolute and relative measures of its performance.

MODEL DEVELOPMENT

This section discusses the mathematical and theoretical development of AIRPOL-4 only; information regarding the development of CALAIR and HIWAY respectively is found elsewhere (1, 2). More detailed information concerning the development of AIRPOL-4 can be found in another report (3).

Basic Formulation

The basic geometry and calculus necessary to express CO concentrations at a receptor, either upwind or downwind of a uniform continuous line source, by using a Gaussian formulation are discussed below. The discussion assumes an understanding of the basic Gaussian formulation.

Figure 1 contains two Euclidian coordinate systems; a roadway, assumed to be a uniform continuous line source; a receptor downwind of the roadway; and a wind direction vector. The receptor coordinate system, or the P, DIST, Z system, is aligned so that the DIST axis is parallel to the wind direction vector with positive DIST measured upwind. The positive Z axis emanates from and is perpendicular to the surface of the earth. Within this system, the receptor coordinates are $(0, 0, z)_{\text{receptor}}$. The roadway coordinate system, or the D, R, H system, is oriented so that the R axis coincides with the roadway, the positive H axis emanates from and is perpendicular to the earth's surface, positive D is measured on the downwind side of the roadway, and the receptor lies in the DH plane. The observer location relative to this system is $(d, 0, z)_{\text{roadway}}$.

Given this information and α, the acute angle between the roadway and the wind vector, it can easily be determined that the roadway coordinate system may be mapped into the receptor coordinate system by

$$p = -d \times \cos(\alpha) + r \times \sin(\alpha) \tag{1}$$

$$\text{dist} = d \times \sin(\alpha) + r \times \cos(\alpha) \tag{2}$$

and

$$z = h \tag{3}$$

This technique allows the total CO concentration at a receptor to be expressed as a simple integral of all roadway points having nonnegative DIST coordinates, i.e.,

$$\text{CO} = \frac{Q_L}{2\pi\mu} \int_M^{\text{ULENGH}} \frac{\exp\left[-\frac{1}{2}\left(\frac{p}{\sigma_p}\right)^2\right]}{\sigma_p} \times \left\{ \frac{\exp\left[-\frac{1}{2}\left(\frac{z-h}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+h}{\sigma_z}\right)^2\right]}{\sigma_z} \right\} dr \tag{4}$$

where Q_L is the uniform line-source emission rate.

The upper bound of integration ULENGH is the distance the roadway extends, in a nearly straight line, upwind from point $(0, 0, h)_{\text{roadway}}$. The lower bound M is found by first determining M′, the distance between $(0, 0, h)_{\text{roadway}}$ and $[0, -d \times \tan(\alpha), h]_{\text{roadway}}$, the intersection of the R and P axes. The latter point is the natural lower bound of integration since, as equation 2 demonstrates, it is the greatest lower bound of all roadway points having nonnegative DIST coordinates in the receptor coordinate system. However, the possibility that this point will lie farther along the R axis than the road actually extends must be accounted for. Since the receptor is downwind of the road, which implies $d \geq 0$, and since $0 \text{ deg} \leq \alpha \leq 90 \text{ deg}$, equation 2 requires that $M' \leq 0$. Therefore M must be defined as M = max (M′, -DLENGH), where DLENGH is the distance the roadway extends in a nearly straight line downwind from the point $(0, 0, h)_{roadway}$.

Figure 2 shows the geometry for a receptor upwind of a roadway. We can see that equations 1, 2, and 3 again transform any roadway point in the roadway coordinate system into the receptor coordinate system. Thus equation 4 may be used to determine the total pollution at an upwind receptor when the bounds of integration are chosen to include only those roadway points having nonnegative DIST coordinates.

ULENGH is determined in the upwind receptor case as it was in the downwind receptor case, by simple specification. The point $[0, -d \times \tan(\alpha), h]_{roadway}$, the intersection of the R and P axes, is again shown by equation 2 to be the greatest lower bound of all roadway points having nonnegative DIST coordinates. However, since the receptor is now upwind of the road, which implies $d \leq 0$, equation 2 shows that M′, the distance from $(0, 0, h)_{roadway}$ to $[0, -d \times \tan(\alpha), h]_{roadway}$, must be $M' \geq 0$. Therefore M for an upwind receptor must be defined as M = min (M′, ULENGH).

Consideration of the upwind formulation versus the downwind formulation reveals that, for the same absolute roadway to receptor distance, $|d|$, $M_U \geq M_D$. For any roadway point contained in both intervals, $p_U^2 \geq p_D^2$ and $dist_U \leq dist_D$. Only when $\alpha = 0$ deg does $M_U = M_D$, $p_U^2 = p_D^2$, and $dist_U = dist_D$. This is reassuring since the upwind and downwind sides of a roadway should be indistinguishable at $\alpha = 0$ deg.

We have shown that a single Gaussian formulation exists that is capable of expressing CO concentrations at receptor points either upwind or downwind from a uniform continuous line source.

Evaluation of Gaussian Line-Source Formulation

Equation 4 has no analytical solution, and solutions using general purpose numerical techniques are excessively expensive. AIRPOL-4 circumvents this problem by using a specialized segmentation technique in conjunction with Cote's method (6) of order six, C6, to solve equation 4.

Careful analysis of the integrand in equation 4 reveals that accurate numerical integration is difficult in only two neighborhoods, $p \simeq 0$ and $r \simeq M$. Thus AIRPOL-4 uses an interval segmentation technique that divides the total integration interval into 12 subintervals. Two of these subintervals cover the interval from M to M + 2, and 10 cover the remaining interval of integration with 5 on either side of the point p = 0. The lengths of these 10 subintervals increase away from the point p = 0 in the ratio of 1:2:3:5:10 with maximum constraints of 10, 20, 30, 50, and ∞ m. When the point p = 0 is not an element of the interval of integration, the midpoint of the interval is used to locate these subintervals. This technique in combination with C6 produces a maximum allowable error of 0.02 ppm (0.02 mg/m^3) of CO with a safety factor of about two orders of magnitude for a superposition of three line sources and yet requires the calculation of only 72 points.

Atmospheric Stability and Gaussian Dispersion Parameters

AIRPOL-4 uses a slightly modified Pasquill method of atmospheric stability classification (7) based on its superiority to the Turner classification method. AIRPOL-4 determines preliminary approximations to σ_y and σ_z by extrapolating Pasquill's empirical curves (8) to the points $\sigma_y = 3.0$ m and $\sigma_z = 1.5$ m and then by shifting these curves left such that $\sigma_{y_0} = 3.0$ m and $\sigma_{z_0} = 1.5$ m. AIRPOL-4 then translates these preliminary values, which are applicable only to rural areas and 3 to 10-min sampling times, to values applicable to urban areas and a sampling time specified by the user. This translation is based on Turner (5, 9) and empirical results obtained from the present study.

Figure 1. Geometry for downwind receptor.

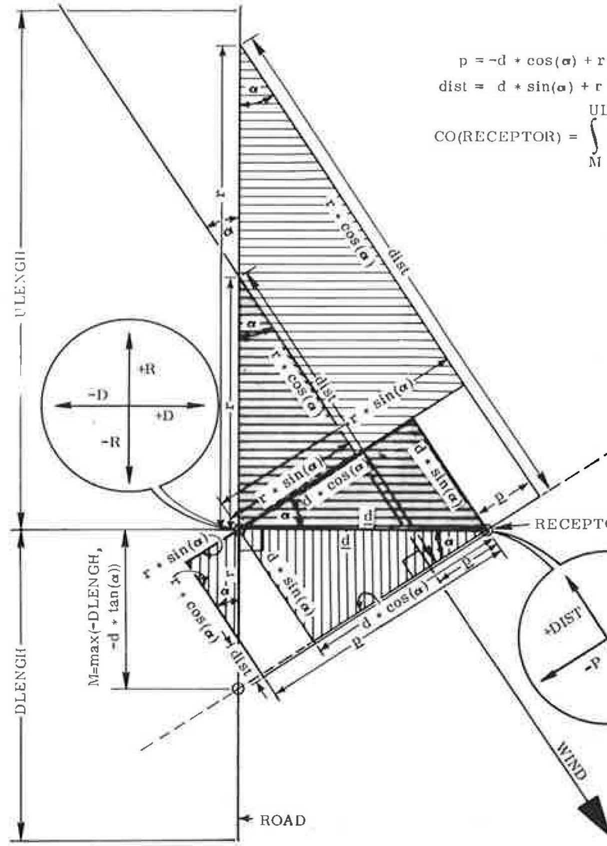
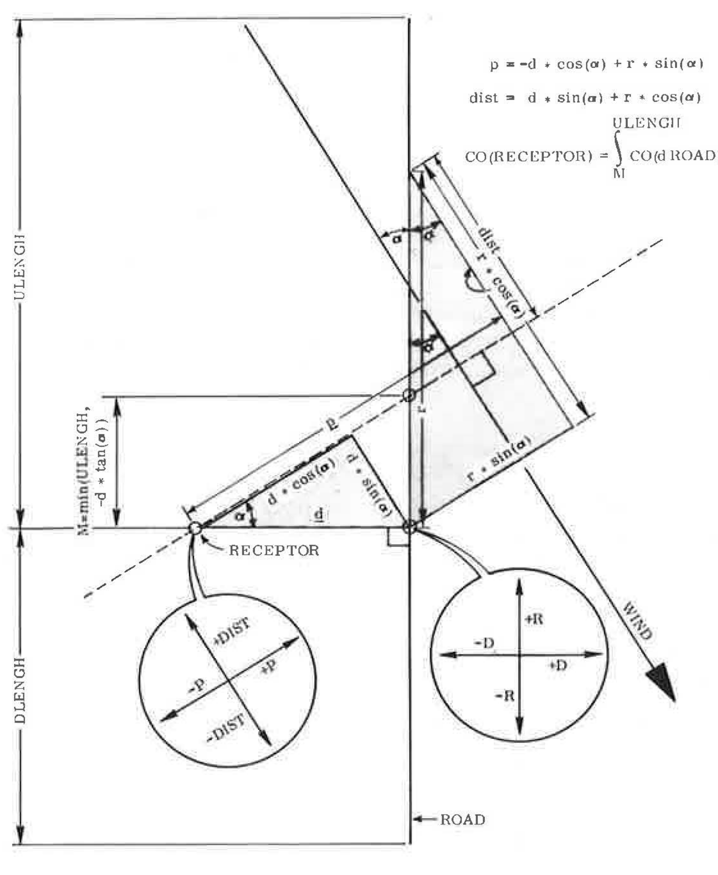


Figure 2. Geometry for upwind receptor.



Wind Speed Dilemma

The basic Gaussian dispersion theory is based entirely on the effect of macroscale air movement and its induced eddy effects exclusive of localized-eddy and molecular dispersion effects. Therefore, this theory indicates an inverse linear relationship, CO $\propto (1/\mu)$, between wind speed and pollutant levels when examined in the context of a mass balance. This relationship, however, requires that CO asymptotically approach infinity as μ approaches zero. This situation is, of course, intuitively and empirically false.

Field data verify that, although an inverse linear relationship yields reasonable predictions at higher wind speeds (greater than approximately 3 m/s), it produces progressively poorer estimates as wind speeds decrease (4, 10). The reason for this behavior is that, as wind speeds decrease, the dispersion effects of molecular diffusion, vertical thermal transport, and localized mixing replace the decreasing dispersion effects produced by macroscale air movement.

Empirical modeling of this residual turbulence concept resulted in the relationship

$$\mathrm{CO} \propto [\mu + 1.92 \times \exp(-0.22 \times \mu)]^{-1} \qquad (5)$$

which produces accurate CO predictions over the entire range of feasible wind speeds. Note that equation 5 specifies that CO becomes inversely proportional to μ for $\mu > 3$ m/s.

Treatment of Elevated Roadways

Although the Gaussian formulation is capable of analyzing elevated sources, it is not directly capable of analyzing highway fill sections. The basic Gaussian stack equations assume that a smokestack does not materially obstruct or alter air flow. A fill section of highway does, however, drastically alter surface wind flows since it forms a physical barrier over which air must circulate.

Wind flows over barriers produce vertical turbulence to a height of 1.5 to 2.0 times the height of the barrier (19). Thus, AIRPOL-4 models the effect of a highway fill section, HEIGHT in meters, by increasing σ_{z_0} to

$$\sigma_{z_0} = 1.5 + \mathrm{HEIGHT}/4 \qquad (6)$$

which in turn increases all σ_z values by shifting Pasquill's σ_z curves to the right. Note that this modification accounts for only the increased vertical turbulence produced at the top of a fill and does not account for the eddies formed on the downwind and upwind slopes of the fill. Thus AIRPOL-4, or any other Gaussian model, will still underpredict CO levels for receptors within about $10 \times \sin(\alpha) \times$ HEIGHT meters of a fill.

Treatment of Depressed Roadways

AIRPOL-4 has been designed to analyze receptors either inside or outside a highway cut section. However, since no test data are available for geometries of depressed roadways, these aspects of the design of AIRPOL-4 have been omitted from this paper.

ANALYSIS OF PREDICTIVE PERFORMANCES

This section analyzes and compares the predictive performances of AIRPOL-4, CALAIR, and HIWAY relative to each other and relative to 436 one-hour field measurements. AIRPOL-4 is completely analyzed with respect to both the Pasquill and Turner stability classes to firmly establish AIRPOL-4 (Pasquill) as the superior version, although CALAIR and HIWAY are analyzed only with respect to the recommended Turner class.

Field Study

The AIRPOL project included a field study to collect data for validating the performance of AIRPOL-4. This study produced simultaneous measurements of CO levels and geometric, traffic, and meteorological parameters. One-hour data samples were measured intermittently at five test sites on random weekdays during either peak or off-peak hours over a period of approximately 1½ years to ensure representative ranges of geometric, traffic, and meteorological variables. During each test, several 1-hour bag samples were collected simultaneously on both sides of the roadway at distances ranging from 3.7 to 117.4 m from the edge of pavement and at elevations of 1.5 and 3.0 m above ground level; 3.0-m samples were taken only adjacent to the roadway.

Test Sites

An attempt was made to locate test sites typifying at-grade, fill, and cut sections of roadway meeting the following criteria:

1. Volume of traffic sufficient to produce detectable levels of CO,
2. Volume of traffic constituting the most significant source of CO in the immediate vicinity,
3. Terrain relatively free of physical barriers such as large buildings,
4. Adequate safe working area for personnel, and
5. Legal and physical accessibility to personnel and equipment.

Subject to these constraints, only one elevated and four at-grade satisfactory test sites were found. Since most of the major highway cut sections in Virginia are in sparsely traveled areas, no satisfactory test sites could be found for depressed roadways. The five selected sites and their measured data ranges are given in Table 1. Percentage breakdowns of the meteorologic and traffic conditions for all test sites are given in Table 2. Figures 3 through 7 show sites 1 through 5 respectively.

Data Collection

Meteorologic

Wind speeds and directions were measured continuously during each test hour by using a vectorvane and were recorded on strip-chart recorders. The strip-chart traces were manually digitized, and data were averaged over hourly intervals. The vectorvane was calibrated in a wind tunnel operated by the Department of Environmental Sciences, University of Virginia. At each of the test sites, the vectorvane was separated from the nearest of any physical obstructions that were present by a distance at least five times the height of the obstruction. The elevation of the vane was always 10 m above the ground.

Information such as cloud covers and ceiling heights needed for atmospheric stability classification was obtained for each 1-hour test interval from National Weather Service offices located at nearby airports. Each of the sites is within 12 km of a National Weather Service office. The atmospheric stability for each test period was determined by the classification schemes of both Turner (11) and Pasquill (7).

Table 1. Site, observed traffic, and meteorologic data.

Item	Site 1	Site 2	Site 3	Site 4	Site 5
Highway	I-495	I-64	I-95	I-264	I-64
County	Fairfax	Norfolk	Fairfax	Norfolk	Norfolk
U.S.G.S. topographic quadrant, 7.5-min map	Alexandria, Va.; D.C.; Md.	Kempsville, Va.	Annandale, Va.	Kempsville, Va.	Little Creek, Va.
UTM map coordinates, km					
North	4296.69	4081.07	4296.52	4078.23	4083.96
East	318.58	393.46	312.90	389.08	390.04
Relative highway elevation, m	0	0	0	10.7	0
Number of lanes	3,3 =6	3,3= 6	4,2,4 = 10	3,3 = 6	3,3 = 6
Median width, m	11.3	18.3	6.4 each	12.8	18.3
General highway direction	East-west	North-south	North-south	East-west	North-south
Land use	Low density, residential	Agricultural, two schools	Light commercial	Low density, residential, light industrial	Low density, residential
Distance to nearest significant external source, m	750	500	300	850	600
Traffic volume range, vehicles per hour					
Low	2,646	3,288	4,510	3,030	2,200
High	7,910	5,190	8,250	5,060	6,650
Traffic speed range, km/h					
Low	61	82	85	80	72
High	100	93	87	90	97
Range of percentage of heavy-duty vehicles					
Low	5	5	4	1	2
High	22	9	11	15	21
Road-wind angle range, deg					
Low	4	20	10	54	21
High	86	20	90	85	88
Wind speed range, m/s					
Low	0.18	1.88	0.58	2.19	0.27
High	4.83	3.08	2.06	3.22	3.80
Turner stability range					
Low	A	B	A	B	B
High	D	C	D	D	D
Pasquill stability range					
Low	A	B	A	A	B
High	D	C	B	C	C

Table 2. Percentage breakdown of experimental conditions.

Parameter	Range	Percent
Road-wind angle, deg	$0 \leq \alpha \leq 30$	27
	$30 < \alpha \leq 60$	35
	$60 < \alpha \leq 90$	38
Wind speed, m/s	$0.0 \leq \mu \leq 0.9$	21
	$0.9 < \mu \leq 1.8$	31
	$1.8 < \mu \leq 2.7$	25
	$2.7 < \mu$	23
Atmospheric stability class[a]	A	6, 10
	B	29, 63
	C	17, 17
	D	48, 10
Total traffic volume, vehicles per hour	$2,000 \leq v \leq 5,000$	58
	$5,000 < v \leq 8,000$	40
	$8,000 < v$	2
Traffic speed, km/h	$56 \leq s \leq 72$	4
	$72 < s \leq 88$	47
	$88 < s \leq 100$	49
Percentage of heavy-duty vehicles	$0 \leq h \leq 10$	65
	$10 < h \leq 20$	34
	$20 < h$	1

[a] Turner and Pasquill.

Figure 3. Site 1.

Figure 4. Site 2.

Traffic

Traffic information such as volumes, vehicle mixes, and speeds was measured at the sites during each of the hourly study periods. Traffic speeds were measured by radar and recorded on strip charts, from which hourly average speeds were manually reduced. The radar units were calibrated with tuning forks before use each day and after every 2 hours of continuous use. Traffic volumes and mixes were determined by manual counts. Vehicles with three or more axles or two-axle vehicles having a capacity of 2000 kg or more were considered to be heavy-duty vehicles; all others were considered to be passenger cars.

Site Geometric

Geometric data such as median, lane, and shoulder widths and roadway elevations were obtained from construction plans. The locations of receptor points were identified by measuring perpendicular distances from pavement edges and heights above ground. Line-source distances were obtained from topographic maps of the site areas.

Carbon Monoxide

One-hour air bag samples were collected simultaneously at several locations on both sides of the highway sites during each test hour and analyzed for CO by using a gas chromatograph. The chromatograph provided a precision of ±1 percent of full-scale setting, or ±0.1 ppm (0.115 mg/m^3) of CO for the 10-ppm (11.5-mg/m^3) full-scale setting used in this study.

The chromatograph was calibrated each day with span and zero gases. Even though these gases had certified CO concentrations, bag samples were taken from each tank before use for analysis by the Virginia State Air Pollution Control Board district office for added assurance.

Analyses

The meteorological, traffic, and physical site data taken for each test period were used as inputs to CALAIR, HIWAY, AIRPOL-4 (Turner), and AIRPOL-4 (Pasquill). Each of the models used emission factors derived from Virginia statistics in accordance with the procedure recommended by EPA (12).

The predicted CO concentrations were then compared with the measured values. The predictive powers of AIRPOL-4 (Turner), AIRPOL-4 (Pasquill), CALAIR, and HIWAY are evaluated in this paper based primarily on three criteria. The first and most important of these is the average squared error of prediction, which is often translated as an error bound. This criterion is the single most powerful test for model comparison since it yields a maximum likelihood measure of the discrepancy between observed and predicted behavior. The second and next most important performance measurement used is a comparison of the regression data generated by fitting the observed and predicted CO data to the SI statistical equation, OBSERVED = A × PREDICTED + B. These regression data indicate which models most closely approximate the ideal behavior, OBSERVED = PREDICTED, in their average performance. The third criterion used in this analysis is the 100 percent confidence limit on the prediction error. This test is demanding because it concentrates on the extreme behavior of the models as opposed to the average behavior; however, a measure of the extremes of a model's eccentricities is valuable to the potential user.

All tests for statistical significance were carried out at a 0.05 significance level. The tests for superiority of average squared errors (and all its transforms) and 100 percent confidence limits were one-sided F-tests of the hypothesis, H_0: average squared error of A > average squared error of B. The tests for regression lines were based

Figure 5. Site 3.

Figure 6. Site 4.

Figure 7. Site 5.

Table 3. Overall predictive performances of models for downwind receptors and upwind receptors.

Statistic	Downwind Receptors				Upwind Receptors	
	AIRPOL-4 (Turner)	AIRPOL-4 (Pasquill)	CALAIR (Turner)	HIWAY (Turner)	AIRPOL-4 (Turner)	AIRPOL-4 (Pasquill)
Number of data points	254	254	225	254	182	182
Average prediction error	-0.22	-0.45	0.75	0.55	-0.31	-0.31
Average squared error	1.28	1.16	5.02	7.22	0.58	0.50
Probable error	±0.76	±0.72	±1.50	±1.80	±0.51	±0.47
Correlation coefficient, percent	42	51	39	31	62	69
Regression slope	0.54	0.96	0.17	0.13	0.85	1.08
Regression intercept	0.70	0.49	0.83	1.02	0.35	0.29
Minimum error	-4.71	-4.71	-3.94	-4.36	-3.94	-3.94
Maximum error	3.81	1.41	13.38	20.05	3.15	1.20
100 percent error range	8.52	6.12	17.32	24.41	7.09	5.14
Minimum observation	0.0	0.0	0.0	0.0	0.0	0.0
Maximum observation	6.50	6.50	5.40	6.50	4.40	4.40
Observation range	6.50	6.50	5.40	6.50	4.40	4.40
Variance of observations	1.30	1.30	1.01	1.30	0.77	0.77
Expected percent within ± 1 ppm	62	65	35	29	81	84
Expected percent within ± 2 ppm	92	94	63	54	99	100

Note: 1 ppm = 1.15 mg/m³ of CO.

on two-sided t-tests of the hypotheses, H_o: slope = 1 and H_o': slope (A) = slope (B).

Model Performance Results

Downwind Receptors

The results of the analysis of model performance for all downwind receptors are given in Table 3. These statistics show the overall superiority of AIRPOL-4 (Pasquill). In particular, Table 3 demonstrates that for AIRPOL-4 (Pasquill) the average squared-error statistic, 1.16, is significantly less; the regression line is significantly closer to the ideal line, OBSERVED = PREDICTED; and the 100 percent error range is substantially less than those for the other models. Note that the CALAIR statistics in Table 3 are based on 29 fewer data points than are those for the other models. This difference results because CALAIR was incapable of analyzing any wind speeds less than 0.9 m/s. This is a reasonably serious deficiency in the model (the 10 percent of the sample points it is incapable of analyzing should reasonably constitute a worst case analysis) and should therefore be considered when examining its effectiveness.

Table 3 also gives the statistical error bounds. AIRPOL-4 (Pasquill) and even AIRPOL-4 (Turner) show comfortable probable errors of ±0.72 and ±0.76 ppm (0.83 and 0.87 mg/m^3) of CO, respectively, compared with ±1.50 ppm (±1.73 mg/m^3) of CO for CALAIR and ±1.80 ppm (±2.07 mg/m^3) of CO for HIWAY. Furthermore, the statistical expectations of the percentages of predictions within ±1 ppm (±1.15 mg/m^3) of CO, 62 and 65 percent, and within ±2 ppm (±2.3 mg/m^3) of CO, 92 and 94 percent, for the Turner and Pasquill versions of AIRPOL-4 are quite respectable and significantly superior to those for CALAIR and HIWAY, 35 and 29 percent within ±1 ppm (±1.15 mg/m^3) of CO, and 63 and 54 percent within ±2 ppm (±2.3 mg/m^3) of CO respectively.

Upwind Receptors

Table 3 also gives the performance results of the Virginia model based on field data for 182 receptors on the upwind sides of source roadways. (Because CALAIR and HIWAY are incapable of producing predictions for receptors upwind from a roadway, they have been excluded from this analysis.) These results firmly establish that AIRPOL-4 (Pasquill) yields reliable predictions of CO levels on the upwind sides of roadways. Specifically, they show that it has an average squared error of only 0.50, which is significantly superior to the Turner result and is certainly comparable to the downwind result. This average squared error translates to a probable error of ±0.47 ppm (0.54 mg/m^3) of CO and an expected prediction error of less than 1 ppm (1.12 mg/m^3) of CO 84 percent of the time and less than 2 ppm (2.3 mg/m^3) of CO almost 100 percent of the time. Furthermore, in its average performance, AIRPOL-4 (Pasquill) behaves almost perfectly. It has a regression slope of 1.08 and an intercept of 0.29 with a correlation of 69 percent. All of these observations demonstrate the statistical superiority of AIRPOL-4 (Pasquill) to the Turner regression results. Table 3 also demonstrates that the 100 percent error range of the Pasquill version is significantly less than that of the Turner version and that the Pasquill version has less of a tendency than the Turner version toward overprediction.

Predictive Performance Results

Relative to Wind Speed

Table 4 gives statistics obtained when the models were analyzed for performance relative to wind speed μ for downwind observers. These results indicate that the performances of all the models are statistically poorer for wind speeds below 0.9 m/s than for those above 0.9 m/s. However, the degradation of AIRPOL-4 is markedly less than that of HIWAY (note again that CALAIR cannot generate predictions for low wind speeds). These results demonstrate that AIRPOL-4 performs reliably even at low wind speeds.

Relative to Wind Angle

Results of the analyses relative to all downwind receptors for different ranges of road-wind angles α are given in Table 4. For 0 deg $\le \alpha \le$ 30 deg, AIRPOL-4 (Pasquill) is statistically superior to the other models. For 30 deg $< \alpha \le$ 60 deg and 60 deg $< \alpha \le$ 90 deg, AIRPOL-4 and CALAIR are nearly comparable; AIRPOL-4 (Pasquill) shows a slight advantage, and HIWAY is significantly inferior. The poor performance of HIWAY for $\alpha \geq 30$ deg is perhaps mitigated by the fact that 10 to 20 percent of the observations for this α range happened to be low wind speeds, for which HIWAY previously has given poor predictions. Similarly, the seemingly acceptable performance of CALAIR for this range of α should be tempered by the fact that the model was incapable of analyzing 10 to 20 percent of the data points.

Relative to Atmospheric Stability Class

Analytical results of the predictive performance of each model relative to stability classes A, B, C, and D for downwind receptors are given in Table 4. Two of the most interesting indirect statistics suggested by these analyses are the distributions of the Pasquill and Turner stability classes. From a total of 48 one-hour sampling intervals (A, B, C, D), distributions of 0.10, 0.63, 0.17, and 0.10 were determined by the Pasquill method, and distributions of 0.06, 0.29, 0.17, and 0.48 were determined by the Turner method. These distributions demonstrate that the Pasquill method tends to yield lower stability classes. Therefore, for urban areas where the atmosphere is more unstable than in rural areas, the Pasquill method should provide better estimates of atmospheric conditions than the Turner method. This is the principal reason for the overall superiority of AIRPOL-4 (Pasquill) over AIRPOL-4 (Turner).

For stability class A, the sample sizes unfortunately are small, but nonetheless they indicate that HIWAY is superior to the other models with respect to average performance characteristics. The analysis for stability class B shows that CALAIR and both versions of AIRPOL-4 are statistically equivalent and superior to HIWAY, which was again hampered by the presence of low wind speeds in 24 percent of the observations. The results of the analysis for stability class C show that the two versions of AIRPOL-4 are statistically equivalent and significantly superior to both CALAIR and HIWAY, and those for stability class D show that AIRPOL-4 (Pasquill) is significantly superior to the three other models.

Relative to Source Elevation

Results of the analyses relative to all downwind receptors for at-grade and elevated sources are given in Table 4. The results for at-grade roadways demonstrate that AIRPOL (Pasquill) is statistically superior to the other models. The results for elevated roadways reveal that the models are statistically equivalent to each other and that none of them performs satisfactorily.

COST PERFORMANCE

The total operating costs for AIRPOL-4, CALAIR, and HIWAY were determined for a typical project analysis consisting of four sites. Fill and at-grade sites were analyzed in a 25:75 ratio, as were source lengths of 1200 and 2000 m. Road-to-wind angles were assigned uniformly from 0 deg $\leq \alpha \leq$ 90 deg. Finally all sites consisted of four-lane, dual-divided facilities with 10.7-m medians and representative peak-hour traffic. Within each site, 16 receptors, 8 each at 0.0 and 1.5-m elevations, extending from 3 to 67 m from the downwind edge of the source road were analyzed. Each receptor was examined under both A and D stability classes for 3 prediction years (each having different traffic and emissions characteristics) at six wind speeds. Thus, a total of 576 receptor concentrations were determined per site.

All three models were bench marked on an IBM 370/158 with 1 megabyte of core running under OS release MFT 21.7 with Hasp II. The programs were all compiled to an object-code library by using an IBM FORTRAN IV, G-level compiler before testing. The machine costs cited are for the execution step only, and there is no system bias in the results.

Table 5 gives the resources required and their dollar equivalents, based on Virginia

Table 4. Predictive performances relative to wind speed, road-wind angle, stability class, and source elevation.

Item	Model	No. of Data Points	Probable Error	Regression Slope	Regression Intercept	Minimum Deviation	Maximum Deviation	Deviation Range
$\mu \geq 0.9$ m/s	AIRPOL-4 (Turner)	225	0.72	0.44	0.73	-4.43	3.81	8.24
	AIRPOL-4 (Pasquill)	225	0.67	0.83	0.56	-4.43	1.23	5.66
	CALAIR	225	1.50	0.17	0.83	-3.94	13.38	17.32
	HIWAY	225	0.90	0.26	0.84	-4.36	6.70	11.06
$\mu < 0.9$ m/s	AIRPOL-4 (Turner)	29	1.03	1.26	0.17	-4.71	1.41	6.12
	AIRPOL-4 (Pasquill)	29	1.04	1.24	0.24	-4.71	1.41	6.12
	CALAIR	—	—	—	—	—	—	—
	HIWAY	29	4.70	0.04	1.17	-2.45	20.05	22.50
0 deg $\leq \alpha \leq$ 30 deg	AIRPOL-4 (Turner)	69	0.75	0.50	0.56	-2.84	3.81	6.65
	AIRPOL-4 (Pasquill)	69	0.59	1.06	0.30	-2.84	1.07	3.91
	CALAIR	67	2.54	0.17	0.65	-0.65	13.38	14.03
	HIWAY	69	1.36	0.29	0.70	-2.01	6.70	8.71
30 deg $< \alpha \leq$ 60 deg	AIRPOL-4 (Turner)	90	0.80	0.87	0.39	-4.71	1.41	6.12
	AIRPOL-4 (Pasquill)	90	0.79	1.06	0.31	-4.71	1.41	6.12
	CALAIR	72	0.71	0.50	0.31	-3.03	2.12	5.15
	HIWAY	90	2.54	0.07	1.13	-3.81	20.05	23.86
60 deg $< \alpha \leq$ 90 deg	AIRPOL-4 (Turner)	95	0.73	0.70	0.69	-4.43	1.00	5.43
	AIRPOL-4 (Pasquill)	95	0.74	0.89	0.66	-4.43	0.83	5.26
	CALAIR	86	0.67	0.65	0.59	-3.94	2.17	6.11
	HIWAY	95	1.09	0.18	0.96	-4.36	7.80	12.16
Stability class A	AIRPOL-4 (Turner)	13	1.44	3.25	-0.80	-4.71	0.16	4.87
	AIRPOL-4 (Pasquill)	25	1.14	2.49	0.01	-4.71	1.03	5.74
	CALAIR	4	1.55	0.76	-1.50	1.86	3.01	1.15
	HIWAY	13	0.77	0.84	0.31	-2.45	2.18	4.63
Stability class B	AIRPOL-4 (Turner)	70	0.83	0.79	0.70	-4.43	1.41	5.84
	AIRPOL-4 (Pasquill)	154	0.75	0.96	0.60	-4.43	1.41	5.84
	CALAIR	53	0.83	0.48	0.71	-3.94	2.44	6.38
	HIWAY	70	3.08	0.07	1.16	-4.36	20.05	24.41
Stability class C	AIRPOL-4 (Turner)	46	0.47	0.74	0.45	-2.14	1.07	3.21
	AIRPOL-4 (Pasquill)	46	0.43	0.76	0.29	-1.62	1.07	2.69
	CALAIR	43	0.94	0.29	0.69	-1.75	4.64	6.39
	HIWAY	46	0.60	0.43	0.74	-2.08	1.91	3.99
Stability class D	AIRPOL-4 (Turner)	125	0.70	0.42	0.61	-4.07	3.81	7.88
	AIRPOL-4 (Pasquill)	29	0.43	1.48	-0.71	-1.92	1.23	3.15
	CALAIR	125	1.84	0.15	0.77	-3.03	13.38	16.41
	HIWAY	125	1.03	0.24	0.72	-3.81	6.70	10.51
At-grade source	AIRPOL-4 (Turner)	214	0.66	0.69	0.40	-4.71	3.81	8.52
	AIRPOL-4 (Pasquill)	214	0.61	1.24	0.09	-4.71	1.41	6.12
	CALAIR	185	1.60	0.20	0.66	-1.61	13.38	14.99
	HIWAY	214	1.90	0.14	0.92	-2.45	20.05	22.50
Elevated source	AIRPOL-4 (Turner)	40	1.15	9.52	-0.04	-4.43	0.13	4.56
	AIRPOL-4 (Pasquill)	40	1.15	10.45	-0.29	-4.43	0.14	4.57
	CALAIR	40	0.92	2.84	0.11	-3.94	0.25	4.19
	HIWAY	40	1.13	5.39	0.53	-4.36	0.15	4.51

Table 5. Cost performances for analysis of four typical sites.

	Resource Requirements			Costs (dollars)		
Resource	AIRPOL-4	CALAIR	HIWAY	AIRPOL-4	CALAIR	HIWAY
CPU time, hour	0.004	0.022	0.565	0.82	4.52	115.80
Cards read	16	4,608	3,294	0.03	7.95	5.70
Lines printed	620	63,936	5,058	0.44	44.76	3.54
Computer memory, K-byte/hour	0.19	1.06	21.46	0.12	0.64	12.88
Input coding, hours	0.22	24.96	14.20	1.16	131.04	74.55
Keypunching, hours	0.05	5.62	3.20	0.18	20.50	11.66
Card stock	16	4,608	3,294	0.02	5.53	3.95
Paper stock, pages	8	2,304	144	0.04	11.52	0.72
Total				2.81	226.48	228.80

Department of Highways and Transportation cost factors, to fully analyze four typical sites. These figures show that the cost of using AIRPOL-4 was only \$2.81 compared to \$226.48 for CALAIR and \$228.80 for HIWAY. Thus the cost of using AIRPOL-4 is only about 1.2 percent of the cost of using either of the other models. In fact, even in those cases where a complete analysis is not desirable for one reason or another, AIRPOL-4 is still superior. For instance, consider the extreme example of four typical sites with only eight receptors per site, all analyzed for a combination of a single elevation, wind speed, stability class, and prediction year. Under these conditions, AIRPOL-4 would still cost only $2.34 compared with $3.15 for CALAIR and $3.18 for HIWAY. Thus, even under these conditions, AIRPOL-4 would cost only about 73.9 percent as much to use as either of the other two models.

Table 5 also demonstrates that CALAIR and HIWAY have nearly unmanageable volumes of input and output but that those for AIRPOL-4 are quite reasonable. Thus, since people are not generally capable of comprehending large volumes of data unless the data are available in some compact and meaningful form, there is an additional cost in using CALAIR or HIWAY that may be measured in terms of the errors and frustration generated by creating and analyzing unnecessarily expanded data sets. These results demonstrate that AIRPOL-4 is clearly a more cost-effective model than either of the other models.

CONCLUSIONS

The results of the statistical comparisons of overall downwind predictive performances have shown that AIRPOL-4 (Pasquill) is superior to AIRPOL-4 (Turner), CALAIR, and HIWAY. For upwind receptors, only AIRPOL-4 can be used, and the Pasquill version is significantly superior to the Turner version.

In the comparison of predictive performances for wind speeds greater than 0.9 m/s, CALAIR and HIWAY performed reasonably well, although AIRPOL-4 (Pasquill) performed better. For lower wind speeds, CALAIR cannot be used at all, and AIRPOL-4 is significantly superior to HIWAY.

AIRPOL-4 (Pasquill) is statistically superior to the other models for the road-wind angle range of 0 deg $\le \alpha \le$ 30 deg. However, for 30 deg $< \alpha \le$ 90 deg, all models except HIWAY are about equivalent, and AIRPOL-4 (Pasquill) shows a slight statistical advantage.

For different atmospheric stabilities, AIRPOL-4 (Pasquill) shows a slight superiority over the other models with respect to average performance. The comparison of predicted and observed CO concentrations for elevated roadways showed that all the models performed poorly and thus need improvement. In addition, AIRPOL-4 proved to be significantly less expensive to use than either CALAIR or HIWAY.

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EXPRESSWAY NOISE AND APARTMENT TENANT RESPONSE

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A questionnaire was distributed to tenants living in apartments within 1,200 ft (365.7 m) of an expressway in metropolitan Toronto to determine what aspects of the expressway affected them, positively or negatively, and how important these aspects were, relative to other factors affecting their residential satisfaction. Tenants indicated that travel convenience was the main advantage of the expressway and that disturbance from noise was the main disadvantage. Analysis of moving intentions indicates that the disadvantage of noise outweighs the advantage of travel convenience for those tenants whose apartments have direct exposure to the expressway. As in other research findings, there is no single demographic group that is particularly sensitive to expressway noise, and analysis of moving intentions by rent level indicates that rent reductions do not seem to compensate for noise disturbance. Rental level and occupancy policy thus are not seen as mechanisms for reducing the environmental impact of expressway noise. Minimum setback distances from the expressway and use of apartments with single-loaded corridors so that living units face away from the expressway are suggested as appropriate means of protection from hazards of expressway noise.

•AN important development that has emerged from transportation planning recently is the effort to take into account the effects that new traffic systems may have on the amenities and environmental quality of adjacent areas. Most of the associated research of this kind to date concerns the impact that heavily traveled routes have on the residential areas and scenic landscapes through which they pass (1, 2, 3). These studies deal with residential development and emphasize levels of disturbance to single-family dwellings, possibly in the belief that such environments are most vulnerable to disruption by large new traffic systems (1, 4, 5). One does not have to attend many public meetings concerning expressway routes to encounter the belief, expressed by both homeowners and officials, that apartments should be used to buffer single-family areas from the environmental impact of expressways.

It is commonly believed by planners and city officials that homeowners are more zealous than apartment tenants in seeking to influence local government to protect low-density residential areas. There is also evidence to suggest that those who live in single-family dwellings, whether as owner or tenant, are more likely than those living in apartments to take an active interest in the local community (6). This does not necessarily mean, however, that apartment tenants are less sensitive to their physical surroundings.

This issue becomes increasingly important because, at least in Toronto, which is the laboratory for this study, there seems to be a trend toward locating substantial numbers of apartments adjacent to the expressway system (7). So far there has been little attempt to determine the general nature of the advantages and disadvantages of this pattern. This study represents one effort to obtain a clearer idea of the costs and benefits of locating apartments close to expressways, as seen by the apartment tenants themselves. The purpose of the study was threefold:

1. To determine which of a number of possible attributes or factors associated with expressways had positive or negative impact on residential satisfaction of the tenants,
2. To assess how important these expressway impacts were relative to other kinds

of factors that affected tenants' general satisfaction with their places of residence, and

3. To determine the implications these findings might have for land use policies affecting apartment location and design.

The survey, the nature of the sample of apartment tenants, and the findings are described in the following sections.

SURVEY

Ideally, a project intent on eliciting response to the presence of an expressway under conditions of varying exposure would take into account all types of exposure conditions in choosing a survey sample. Thus, building setback, elevation and orientation relative to the expressway, apartment floor level, presence and effectiveness of screening, and other obstacles would be important factors to consider. However, the scope of this project has limited the exposure characteristics used to choose the initial building sample to two conditions, namely, building setback and orientation. Buildings have been excluded where extensive site screening, other neighboring structures, or extreme changes in level might contaminate these relatively clear-cut conditions of exposure. A third factor, floor level, was used in selecting apartments for questionnaire distribution.

Figure 1 shows the setback and orientation criteria used in selecting buildings. There are three setback zones: near [0 to 150 ft (0 to 45.7 m)], medium [151 to 500 ft (46 to 152.4 m)], and far [501 to 1,200 ft (152.7 to 365.7 m)]. There are two possible building orientations: perpendicular and parallel to the expressway alignment. Finally, building faces are either unscreened or screened, depending on whether there is direct line of sight exposure to the expressway. All screened apartments are located on the blind side of buildings and have a parallel orientation.

Access to Expressway

Setback, orientation, and floor level are indicators of an apartment's location and exposure relative to the expressway. By themselves, however, these measures do not indicate proximity to an expressway access ramp. Only in some cases is this distance positively correlated with setback distance. In particular, buildings that are physically close to the expressway right-of-way do not necessarily have better accessibility to the expressway than those that are more distant. Three sets of driving distances to the nearest ramp were used in defining the relative accessibility of buildings in the sample: high, 0 to 1,999 ft (0 to 609.2 m); medium, 2,000 to 4,999 ft (609.6 to 1523.6 m); and low, 5,000 ft (1524 m) or more.

Determining Building Face Sample

Attempts were then made to select an adequate sample of buildings that had faces representing all of the 27 possible combinations of setback, orientation, and accessibility and that had no intervening obstacles between the apartment building and the expressway. There were only 37 buildings of the 512 available that satisfactorily met these criteria, and this number was further eroded when it was not possible to obtain permission to enter some buildings for purposes of the survey. Ultimately, the sample contained 23 buildings representing 20 of the possible 27 combinations.

Respondents within the buildings were chosen by a predetermined nonrandom sample procedure designed to ensure that various floor levels and positions along building faces were represented in the sample. Of the 1,000 questionnaires distributed, 795 returns were received, for an overall response rate of nearly 80 percent.

FINDINGS

The questionnaire attempted to determine which of a number of possible factors associated with the expressway were important to the apartment tenants. Analysis of the results showed that the two major factors were traffic noise and travel convenience.

Location within the expressway corridor does have serious disadvantages for the residents; almost 60 percent of the sample reported being disturbed or severely disturbed by noise. For tenants living along unscreened building faces, disturbance increased systematically as proximity to the expressway increased. Of the tenants living in the buildings in the far setback positions, almost 50 percent reported that they were disturbed by noise. This proportion increased to 75 percent for those living in the near setback positions. These relationships are given in Table 1 for tenants living along unscreened and screened building faces. Reports of disturbance from noise, although appreciable, are substantially lower along screened building faces and do not indicate a clear-cut relationship to distance from the expressway.

There is evidence of substantial disturbance from expressway noise, and it is appropriate to ask whether living in an apartment in the expressway corridor provides any compensating travel advantages that might offset the disadvantage of noise and to try and determine what proportion of the sample derives travel benefits from the expressway. Over 33 percent of the sample used the expressway for less than one-quarter of all vehicular trips, and 14.1 percent indicated no expressway use at all.

Proportion of Vehicular Trips on Expressway	Responses (percent)	Proportion of Vehicular Trips on Expressway	Responses (percent)
0	14.1	$\frac{1}{2}$	9.5
$<\frac{1}{4}$	23.4	$\frac{2}{3}$	8.3
$\frac{1}{4}$	8.4	$\frac{3}{4}$	13.1
$\frac{1}{3}$	4.2	All or almost all	19.0

It seems reasonable to conclude that there is a significant minority of tenants living in the expressway corridor for whom the expressway is of limited benefit.

One should also find out whether those who do use the expressway extensively (for more than one-half of their trips) are less likely to report disturbance from noise than those who do not use it extensively. Those who do use the expressway are less likely to report disturbance although we cannot be certain whether the lower level of disturbance among expressway users stems from a reduced perception of disturbance or from a greater reluctance to report disturbance (Table 2). In either case, the results suggest that expressway users in some manner take account of travel convenience in reporting disturbance from noise. The corollary to this, however, is that the reported noise problem for those making less extensive use of the expressway is more severe than would appear from the overall figures given in Table 1.

Although the data seem quite clear in pointing to a high level of noise disturbance for apartment tenants in the expressway corridor, it is useful to ascertain how important this disturbance is in their general assessment of residential satisfaction. The survey included a question concerning moving intentions of residents when their leases were up. The possible responses were yes, considering it but no definite plans, and no. Although moving is not per se an indicator of dissatisfaction, differences in the proportion planning to move may reasonably be considered as a rough indicator of relative satisfaction with the residential environment. Use of this indicator enables the researcher to get some sense of the degree of importance that the respondents attribute to the advantages of travel convenience and the disadvantages of noise relative to other factors influencing their evaluations of their living environment.

Along unscreened faces (Table 3), there is a definite and consistent relationship between noise disturbance and moving intentions in all three setback categories. Moving

Figure 1. Exposure classifications.

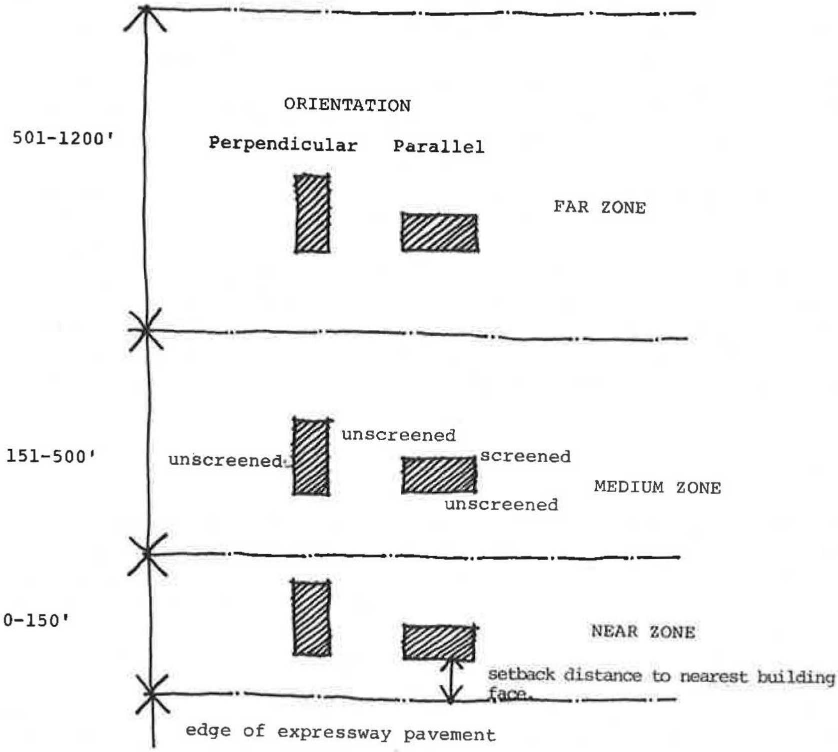

Table 1. Percentage of residents disturbed by noise related to building setback.

Setback	Severely Disturbed	Disturbed	Not Disturbed
Screened face			
Near	25.9	13.6	60.5
Medium	26.3	28.9	44.7
Far	14.3	23.4	62.3
Avg	21.4	20.4	58.2
Unscreened face			
Near	46.6	29.3	24.1
Medium	40.5	30.8	28.6
Far	20.8	27.6	51.6
Avg	35.9	29.2	34.9

Table 2. Percentage of residents disturbed or very disturbed by noise related to building setback and expressway use.

Setback	Expressway Use Low[a]	Expressway Use High[b]	Setback	Expressway Use Low[a]	Expressway Use High[b]
Screened face			Unscreened face		
Near	48.5	30.3	Near	82.1	71.2
Medium	61.1	50.0	Medium	78.7	62.8
Far	40.4	23.1	Far	49.1	46.7

[a] < ½ of all vehicular trips. [b] > ½ of all vehicular trips.

intentions are somewhat reduced in the near setback category as use is increased, but this does not hold in the other two setback categories. An interesting reversal of this general pattern occurs along screened faces (Table 3), where there is no consistent relationship between noise disturbance and moving intentions. However, there appears to be a definite relationship between expressway use and moving intentions: In the near and medium setback positions, the percentage of residents planning to move decreases as expressway use increases. In the far setback position, the percentage of residents planning to move increases markedly as expressway use increases.

Evidently, on the screened side of buildings, whatever respondents may have said about noise disturbance does not appear to be the overriding factor in their general assessment of the residential environment. One can speculate that these respondents may have sensed that, even though they personally were disturbed by noise, the level of noise they were exposed to was not that different from many other places in the city. In this case, moving would be less likely to be seen as a solution. Along unscreened building faces, however, it would certainly appear not only that noise is an important factor but also that it outweighs any advantage that may accrue from expressway use.

POLICY GUIDELINES

Based on the extent of the noise problem and its relative importance to respondents, we attempted to determine what the survey suggested in the way of policy recommendations. First, the survey suggests there has been a self-selection process whereby extensive expressway users have located themselves close to the expressway (Table 4). However, as we have seen, for those living in unscreened apartments, expressway noise is more important than expressway use, and this implies that, even for expressway users, a location near the expressway may not be advantageous. There is additional evidence that those making extensive use of the expressway have tended to choose locations close to the expressway, even though this has not necessarily enhanced their accessibility to an expressway ramp (Table 5); i.e., apparently some expressway users have made apartment location decisions on the basis of presumed travel convenience without considering the noise hazard or the real accessibility that their choice of location provides. Thus, although one could say that expressway users demand locations close to the expressway, it would be hard to argue that apartments in such locations are justified because of that demand, unless real (as opposed to apparent) accessibility is particularly good. Even here the costs may outweigh the benefits. Certainly, apartments close to an expressway hold no advantage for those not making extensive use of it. On the whole, although there may be some reasons for placing apartments close to expressways, the advantage for expressway users does not appear to be one of them.

Second, the survey lends no support to the notion that some groups defined in demographic or social terms are less sensitive to noise than others. Based on apartment location and presence or absence of screening, there is no social or demographic category that consistently has the highest proportion of respondents disturbed by noise (7). This is consistent with other research findings on this subject (8). (Lining the expressways with bachelor flats will not do.)

Third, the survey lends no support to the idea of providing lower rent accommodation near the expressway so that reduced rent can balance out the environmental disadvantage. Building managers were requested to provide us with average rentals for various sizes of apartments in their buildings. The data for two-bedroom units were used since they were most nearly complete. It was evident from these data that building rentals tended to be lower as proximity to the expressway increased; this suggests that the market had taken some account of expressway effects. However, there is no indication that the level of rents charged provides compensation for adverse environmental influences (Table 6). In low-rent buildings, the relationship between noise disturbance and moving intentions is stronger than in high-rent buildings for those tenants living along unscreened building faces. As before, for tenants living on the screened side of buildings there is no consistent relationship between noise and moving intentions.

It would appear, then, that the only approach to ameliorating this particular environ-

Table 3. Percentage of residents within setback categories who plan to move related to noise disturbance and expressway noise.

Setback	Disturbed by Noise	Not Disturbed by Noise	Low Expressway Use	High Expressway Use
Screened face				
Near	26.7	24.5	32.3	20.9
Medium	28.6	29.4	44.4	21.1
Far	13.8	6.5	4.2	20.2
Unscreened face				
Near	44.0	25.6	44.2	36.4
Medium	37.3	24.5	30.4	36.3
Far	28.3	18.4	21.2	22.4

Table 4. Number of residents by setback who use expressway.

Setback	Expressway Use		Setback	Expressway Use	
	Low	High		Low	High
Unscreened faces			Screened faces		
Near	77	107	Near	31	43
Medium	79	91	Medium	18	19
Far	113	76	Far	48	25

Table 5. Percentage of residents who use expressway extensively related to setback and accessibility.

Setback	Accessibility		
	High	Medium	Low
Near	68.0	64.4	45.5
Medium	52.4	56.8	47.4
Far	39.2	—	39.1

Table 6. Percentage of residents who plan to move related to rent and disturbance from noise.

Rent	Not Disturbed by Noise	Disturbed by Noise	Rent	Not Disturbed by Noise	Disturbed by Noise
Unscreened faces			Screened faces		
Low[a]	28.8	47.1	Low[a]	20.0	21.4
High[b]	17.1	29.5	High[b]	11.3	18.8

[a] < \$180/month for two-bedroom unit. [b] > \$180/month for two-bedroom unit.

Table 7. Percentage of residents disturbed by noise related to setback and building orientation.

Setback	Orientation	Severely Disturbed	Disturbed	Not Disturbed
Near	Unscreened parallel	54.5	22.7	22.7
	Unscreened perpendicular	35.8	38.3	25.9
	Screened parallel	25.9	13.6	60.5
Medium	Unscreened parallel	37.0	40.7	22.2
	Unscreened perpendicular	41.1	29.1	29.7
	Screened parallel	26.3	28.9	44.7
Far	Unscreened parallel	20.6	27.7	51.6
	Unscreened perpendicular	21.6	27.0	51.4
	Screened parallel	14.3	23.4	62.3

Table 8. Percentage of residents disturbed by noise related to setback and floor level.

Setback	Floors 1 to 6	Floors 7 to 12	Floors 13 to 26
Screened face			
Near	56.8	23.8	26.1
Medium	31.3	68.8	83.3
Far	41.9	37.0	31.6
Unscreened face			
Near	76.4	68.9	82.5
Medium	70.7	73.0	70.0
Far	43.8	43.5	65.9

mental hazard lies in land use and design controls. In this area, the survey provides some evidence that can assist in forming guidelines.

1. Unscreened building faces were divided into two types: those parallel with and those perpendicular to the expressway. Perpendicular orientation provided no consistent advantage in terms of noise reduction over the parallel orientation (Table 7). Since buildings oriented parallel to an expressway have one screened face, they are strongly preferred.

2. There appears to be no consistent reduction in disturbance from noise as the height of apartments above ground is increased (Table 8). Building taller apartments, therefore, does not appear to offer any guarantee that the proportion of tenants experiencing noise disturbance will be reduced.

3. Screening by a building is evidently an effective device for reducing noise disturbance. The level of disturbance reported by tenants living along screened faces in the nearest setback position is comparable with that reported by tenants in unscreened apartments that are furthest removed from the expressway (Table 1).

In view of these observations, we suggest the following design principles:

1. In built-up areas, no buildings with apartments that have a direct view of the expressway should be built within 500 ft (152.4 m) of an expressway.

2. Buildings located closer to an expressway than 500 ft (152.4 m) should only be permitted if they have single-loaded corridors and no living units on the exposed face.

3. Preferably, the nearest zone [0 to 180 ft (0 to 54.8 m)] should contain no residential structures at all.

4. Where expressways extend through land outside built-up areas, residential structures should, where possible, be at least 1,200 ft (365.8 m) from an expressway.

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