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Contents

Foreword

Transportation-related environmental impacts are increasingly the critical determinants in transportation decisions. Noise and air quality are two of the most directly affected factors of transportation. It is therefore imperative that research in this area continue and that the results of studies are reported in a systematic way. The papers in this Record report on selected studies on aircraft, highway and rail transit noise, and on transportation-related air pollution.

Feitelson questions the way that airport noise mitigation funds are allocated. Although noise maps generally reflect current noise conditions, it is argued that predicted noise forecasts are uncertain. He suggests that it is more efficient to relate mitigation expenditures to monitored noise, rather than forecasted noise. This approach is more equitable, and it shifts the focus of public debate from forecast assumptions to criteria for noise abatement.

Force and Hochman discuss highway noise issues and describe a New Jersey Department of Transportation procedure to evaluate noise impacts for vacant land on which development is planned. Early detection of proposed residential development is essential to avoid delays and costly redesigns. Schuster and Wong report on an investigation of the Pennsylvania Turnpike widening. The project described in the paper involves the installation of extensive noise wall barriers along the Turnpike, which was widened from four to six lanes. At 16 of the 57 sites investigated, the noise level exceeded established noise abatement criteria, and those sites required noise barriers. After studies were completed to compare actual with predicted and existing noise levels, the decrease ranged from 2.9 dBA to 13.0 dBA.

Pendakur and McLean describe their noise impact study of the Vancouver, Canada, Automated Light Rail Transit system. Noise measurements were taken to establish relationships between noise levels and the distance from the guideway, and to relate residents' noise perception to the measured impact. In general, residents' perceptions in the zone of high impact are relatively consistent with the measured noise levels, whereas those in the low-impact zones are somewhat exaggerated. The authors conclude that noise prevention and mitigation of negative impacts must be part of new system planning. Nelson discusses the aerial structure noise reduction effectiveness of resilient rail fasteners based on data collected by the New York City Transit Authority and the Washington Metropolitan Area Transit Authority.

One paper deals directly with air pollution. Wayson and Bowlby present a description of the tools and methodologies available for conducting a detailed, accurate assessment of air pollutant emissions from airport operations. The common pitfalls are discussed along with the methods used to overcome difficulties in estimating emissions.

Koushki analyzes the environmental impact of transportation systems on air quality and noise levels for Riyadh, Saudi Arabia. Findings indicate that traffic-generated noise and carbon monoxide air pollution were in excess of permissible standards by a considerable margin. The author concludes that increased mobility favoring the private mode of travel by responsible authorities has created a significant negative impact on the urban environment.

Some scientists predict that over the next 100 years temperatures will rise 5 to 9 degrees Fahrenheit resulting in a rise in the sea level of 2 to 5 ft. Hyman, Miller, and Walker discuss the possible impacts of such a global climate change on urban transportation. The uncertainty of future temperatures suggests increasing the safety factor currently designed into expansion joints on bridges and major roads, and reexamining the heat tolerances of railroad tracks. Rising sea level could have an extensive impact on cities near the sea. The authors suggest that design standard and siting criteria should be reassessed in light of likely climate changes.

Efficiency, Economic Incentives and Noise Treatment Policy: The Ben-Gurion Airport Experience

ERAN FEITELSON

Aircraft noise is the most prominent negative externality of airports. It has been the main source of community opposition to airport development plans. The current approach to airport noise mitigation emphasizes long-term compatibility. It is based on standards for aircraft noise emissions and the promulgation of airport noise compatibility plans. Such plans are based on computer-generated forecasted noise exposure maps. The validity of noise maps is a function of the validity of the inputs used to generate them. A review of these inputs reveals that their forecasts are subject to inherent uncertainty. Although noise maps reflect current noise conditions accurately, maps depicting noise forecasts are inherently uncertain. Allocating funds for mitigation based solely on such forecasts may thus be inefficient. This paper suggests that relating mitigation expenditures to current noise levels is more efficient. Relating airports' outlays on noise mitigation to the noise effects of their operations provides airports with an economic incentive to operate in a noise-sensitive manner. It may shift the focus of public debate from the assumptions underlying noise forecasts to the criteria for noise abatement, a shift that arguably may help reduce opposition to airport development plans. A number of implementation issues are discussed and the approaches used to deal with these issues in Ben-Gurion Airport are described.

Aircraft noise is the most prominent negative externality of airports. It has been at the center of community opposition to airport development plans throughout the world. Most large airports have noise problems (*1*).

The current approach to aircraft noise mitigation emphasizes long-term compatibility between airports and their surroundings. It is based on reducing noise at the source (aircraft) using emission standards and on the promulgation of airport noise compatibility plans. Such plans are based on noise forecasts. Yet, as this study shows, such forecasts are subject to inherent uncertainties. Consequently, noise mitigation measures based on such forecasts may be inefficient. This paper argues that this pitfall may be overcome by modifying compatibility plans to include a mitigation program based on current noise levels and backed by a monitoring system. Such a program would also provide the airport with an equitable economic incentive for noise-sensitive operations.

The present approach and its limitations are briefly reviewed in the first section. Economic incentives have often been mentioned as alternative or complementary methods for aircraft noise mitigation (*2*). They have been increasingly used in Europe and Japan (*3,4*), but not in the United States (*5,6*). The next section reviews the possible uses of economic instruments for airport noise mitigation. Most studies and applications of noise-related charges focus on the airlines. In the third section, a simple airport-oriented approach to noise mitigation is suggested. This approach is shown to provide an economic incentive for airports to operate in a noise-sensitive manner. Some implementation issues related to this approach are also discussed. The fourth section suggests ways to address the implementation issues. It focuses on the example of Ben-Gurion airport in Israel, where such an approach has recently been adopted.

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CURRENT APPROACH AND ITS LIMITATIONS

The ability to achieve long-term compatibility between airports and their environment is a function of two factors: (a) the ability to reduce noise at the source to offset the growth in volume of operations; and (b) the ability to reduce current population exposure to noise and to prevent population growth in affected areas through operational procedures, zoning, noise insulation, and purchase of land, houses or development rights.

The policies to reduce noise at the source have been based on setting standards that all aircraft would have to meet at specified dates. In the United States, these standards were set in Federal Aviation Regulations (FAR) Part 36; in Europe and the rest of the world they are usually based on International Civil Aviation Organization (ICAO) Annex 16. Toward the end of the 1970s, stricter standards were adopted for third-generation aircraft (FAR 36 Chapter 3, ICAO Annex 16 Chapter 2). The technological limits to source noise reduction have probably been reached with third-generation aircraft. The turnover from stage two to stage three aircraft has been slower than anticipated. Reduction of noise at the source thus has long-term limitations on the extent to which it can offset the additional noise that results from the increasing volume of flights.

To complement the source reduction policy, most countries have suggested and implemented policies to reduce the exposure of population in areas around airports. In the United States, such policies have been suggested in FAR Part 150. The basis for any noise compatibility plan under FAR 150 is a noise exposure map forecasting the noise contours around the airport 5 years in the future. The cost-effectiveness of some measures suggested in FAR 150, such as zoning, insulation, and acquisition of land, development rights or houses in high-exposure areas, depend on the accuracy of the noise exposure map.

Noise maps are generated by computer models. The best known model is the Integrated Noise Model (INM). All models, however, follow the same basic procedure; that is, they require similar inputs and produce similar outputs. The inputs generally required are the number of operations by aircraft type, day or night, for each flight track/runway combination. These inputs, in turn, depend on the following variables:

- Number of daily operations
- Breakdown between day and night operations
- Types of aircraft used
- Runway use patterns
- Takeoff and landing procedures
- Flight tracks
- Flight track usage (a function of the runway used and flight destination)
- Relative weight of aircraft taking off, usually expressed as stage length

The INM model is usually considered accurate. The results, however, are sensitive to changes in inputs (*7*). The accuracy and validity of the noise contours generated by the model are therefore primarily a function of the accuracy and validity of the inputs. If the number of operations or the day/night breakdown of operations is inaccurate, the overall area exposed to noise (above any specified level) would be affected. If runway use pattern, flight tracks or flight track use patterns are misspecified, the noise distribution around the airport will be different from that forecasted. If aircraft types, takeoff and landing procedures, or stage lengths are inaccurate, both the shape of noise contours and the total area covered by them would change. If all the inputs are accurate, noise models generally correspond well to monitored noise. Although the current values of all inputs are usually known, forecasts of most inputs are highly uncertain.

The aforementioned variables can be divided into two groups. The number of daily operations, day/night breakdown, types of aircraft used and destinations (which affect flight track usage and stage length) are primarily a function of decisions made by airlines. These decisions are, in turn, a function of changing local, national, and international market conditions that are subject to great uncertainty (*8*). With the advent of hub-and-spoke operations and the consolidation of the airline industry through mergers, concentration ratios in many hubs increased significantly. That is, a smaller number of airlines are responsible for a larger percentage of the operations. Consequently, the values of these variables are often highly dependent on the routing decisions of a very small number of airlines. It is practically impossible to forecast such routing decisions beyond the immediate future.

Furthermore, in multiple-airport regions the choice of airport by passengers is highly influenced by the availability of direct flights, and is thus also a function of airline routing decisions (*9*). In such regions, the demand for airport services is also a function of actions undertaken by airlines and competing airports in the region, increasing the uncertainty regarding any forecasts of operations in the airport (*10*).

Runway use patterns, flight tracks, and takeoff and landing procedures are decisions airports can influence (*6*). In practice both runway use patterns and flight tracks may change quite often, because they are a function of a host of considerations including the weather, safety, airline demands, and infrastructure limitations. In the Baltimore/Washington International Airport (BWI), for example, 1985 runway use patterns used to forecast noise in the new master plan were obsolete by 1987 (*10*). Consequently, even though these decisions can be affected by the airport, substantial uncertainty exists regarding the values of such variables in the future.

As a result of all these uncertainties, actual noise contours often deviate significantly from forecasted levels. This can be seen in Figure 1, which depicts the 1982 noise zone and 1987 actual 65 Ldn contours of BWI, a typical medium hub (*1*), whose noise forecasts have usually been state of the art (*11,12*). Figure 2 shows the implications of the deviation between forecasts and reality in terms of land area, housing units, and population exposed. In relating the two figures, it is important to note that there were deviations not only in total exposure between forecasts and reality but also in the spatial distribution of housing units affected. Thus, although in some areas the noise levels were higher than forecasted, in others they were lower.

Noise mitigation efforts based on forecasted noise may thus be somewhat misdirected, and consequently inefficient; that is, expenditures may be undertaken on the basis of projected noise levels at sites that ultimately would not be exposed to such levels. At the same time, other untreated sites may be exposed to higher noise levels, ultimately requiring additional expenditures.

ECONOMIC INCENTIVES FOR NOISE MITIGATION

The shortcomings and limitations of the current approach have led several countries to consider the use of various noise-related charges to induce a faster turnover to quieter aircraft, to ensure compliance with noise mitigation procedures and to finance mitigation efforts such as insulation and purchase of houses in noise-stricken areas (*3*). Most noise-related charges discussed and implemented are targeted at airlines. Economic theory suggests that, if set properly, such charges would lead polluters (airlines) to reduce emissions (noise) to the desired level in a cost-effective manner (*2,13*). Setting the charges specified by economic theory, however, would require at least identifying marginal damage functions. Estimates of such functions have often been questioned on both theoretical and empirical grounds (*14*). Alexandre et al. (*14*), having surveyed the various approaches to setting noise charges and the difficulties in implementing them, suggest that a third best approach to set them would be as a function of noise abatement costs in forecasted noise zones, and aircraft types expected to be used during the forecast period. Yet, as discussed in the previous section, both these inputs are uncertain, and thus noise charges set in this manner may also be misspecified.

Economic incentives, however, can also target airports. Currently, airports in the United States have two economic incentives for noise mitigation: litigation by nearby property owners, and federal subsidies for implementing noise compatibility plans.

Litigation is costly. Because communities differ in terms of resources and organization, some communities may be able to litigate more (and better) than others. This gives airports an incentive to avoid the more litigious communities, which may come at the expense of less organized ones. Federal

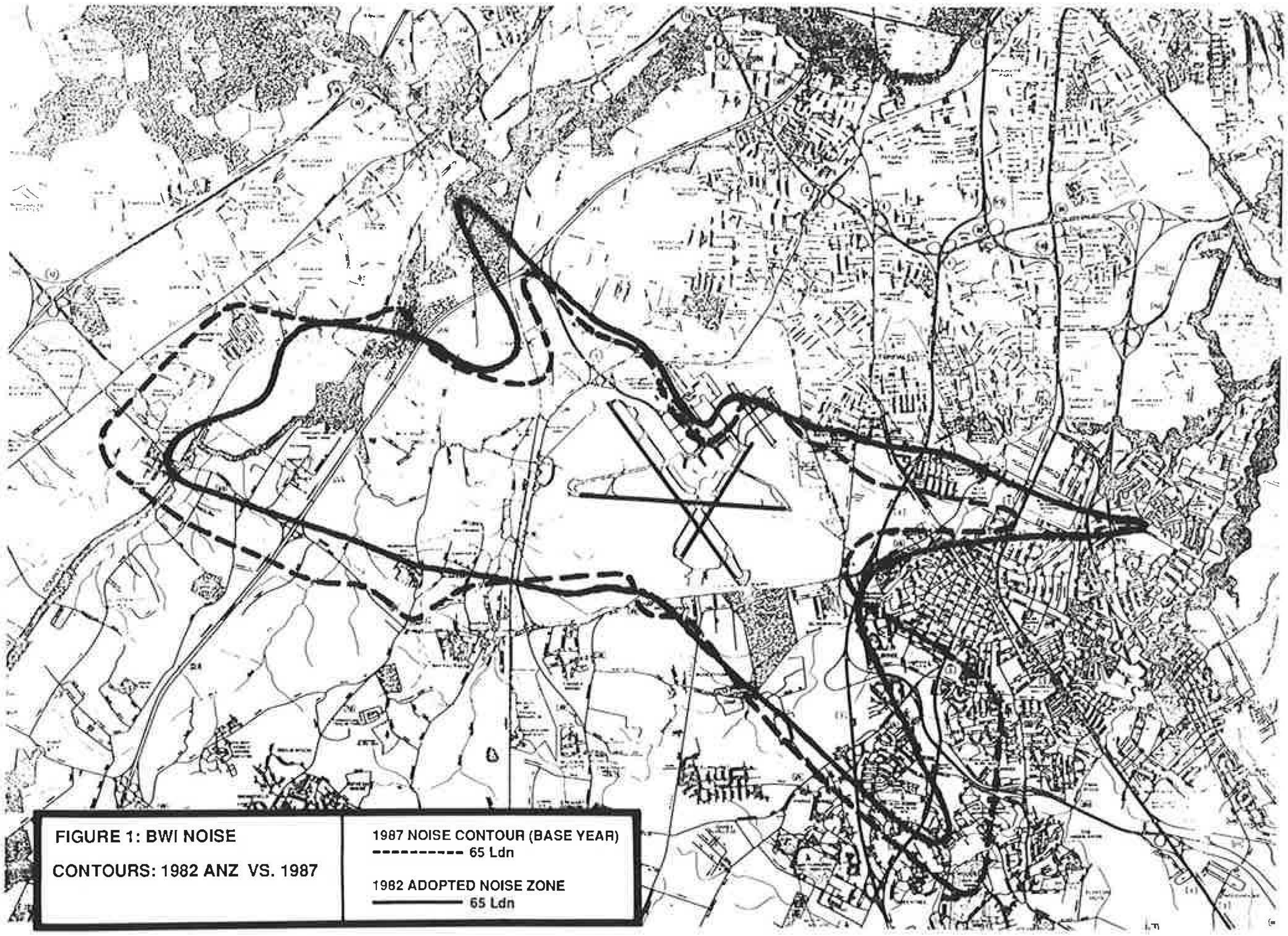

FIGURE 1 BWI noise.

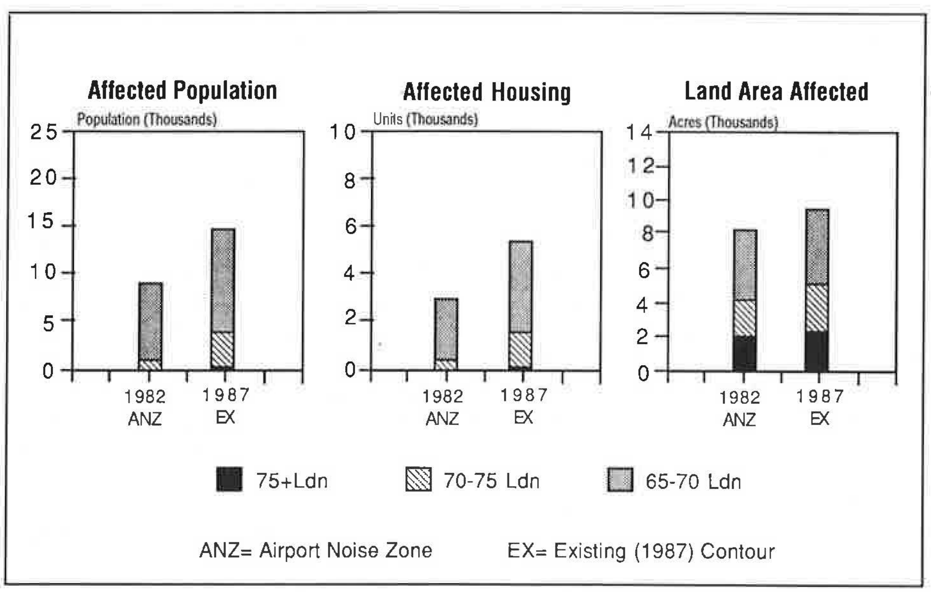

FIGURE 2 BWI noise effects: 1982 forecast vs. 1987.

subsidies are provided for noise compatibility planning and for implementing noise mitigation measures suggested in such plans. Yet, if such measures are based on uncertain noise forecasts, they may be inefficient because they may not be implemented in some areas exposed to high noise levels, while federal funds are used in areas that ultimately will be subjected to lower noise levels.

NOISE TREATMENT AS AN ECONOMIC INCENTIVE

The dependency on noise exposure maps can be avoided by requiring that noise mitigation measures at the receptors be undertaken on the basis of current, rather than forecasted noise levels. Current noise levels can be determined by running a model with current inputs, calibrated and validated by a (limited) monitoring system. Such an approach should not be too difficult to implement because many major airports already have noise units and operate monitoring systems, for calibrating noise forecast models, for evaluating citizen complaints, and for monitoring aircraft compliance with noise-mitigation procedures (*15*). Furthermore, FAR 150 requires the preparation of current noise maps, in addition to 5-year forecasts, as part of the material to be submitted, and the updating of noise maps when significant increases in noise exposure occur.

The noise monitoring system would be used to validate the accuracy of the current model-generated noise map, calibrate the model for local peculiarities (such as terrain), and verify the validity of the inputs (especially pertaining to aircraft behavior). The current, monitor-validated noise map could then be used to evaluate whether any specific area is subject to noise exposure above a prespecified level, entitling it to receive funds in the form of noise insulation, purchase price assurances, moving compensation, or any other combination or form of compensation for the granting of navigation easements. It should be noted that this approach does not preclude the use of noise forecasts as a basis for evaluating airport improvement projects, zoning or purchase of land and development rights. Rather, it is meant to complement the other elements by providing a cost-effective way to deal with the noise problems of existing sensitive land uses.

An important facet of this proposal is its creation of a connection between airport operations and their noise-related expenditures. Measures to reduce flights in a certain area would be reflected in the current noise map for the airport and translated into a reduction in receiver-oriented mitigation costs (such as insulation). If an airport relaxes some of its operation requirements (such as noise abatement flight tracks, landing and takeoff profiles, or slot or capacity limitations), it would face an increase in receiver-oriented mitigation costs. This proposal thus provides the airport with an incentive for operating in a manner that would minimize noise exposure. In a sense it is similar to the incentive provided by litigation, but it is based on costs of noise mitigation (which are a function of exposure) rather than on the costs of litigation.

Relating noise mitigation to current noise may also improve the relationship between airports and their surrounding communities. When noise mitigation policies are based on noise forecasts, the uncertainties inherent in the forecasts often become a source of contention between the airport and various community groups, because such groups challenge the assumptions behind the forecasts. Relating noise mitigation measures to current, monitor-validated noise may shift the focus of discussion to the criteria for action, that is, to the determination of the noise level at which certain noise mitigation action should be taken. The pertinent question thus becomes how tolerable is noise. Studies dealing with this question show that although individual tolerance toward noise varies widely, community reactions are fairly consistent (*16*). Consequently, standards regarding the acceptability of noise levels are similar in most parts of the developed world. Therefore it may be easier to reach an agreement regarding the criteria for noise abatement action than to agree on a noise exposure forecast. Such agreements may help reduce the mistrust that often characterizes airport-community relationships.

Although this approach may seem fairly straightforward in theory, a number of difficult issues have to be addressed before it can be applied.

The first issue is the time span over which noise should be measured before a decision regarding treatment can be made. This issue has a number of facets. First, during this time span residents are exposed to excessive noise levels. The time should be minimized, therefore, to reduce exposure. Second, the length of time should allow for short aberrant runway use patterns attributable to weather or runway conditions; that is, high noises for relatively short, infrequent periods of time should not lead to major outlays on treatment. Third, it would be inefficient to treat areas that can be expected to be relieved as a result of noise reduction at the source, whether through aircraft turnover to stage three or as a result of changes in use patterns (following the construction of a new runway for example).

The second issue is how to relate treatment to zoning variances. It is socially inefficient for an airport to monitor and treat residences that were permitted through a zoning variance, because the airport is adversely affected and public welfare is not improved (*17*). Any application of this approach thus has to differentiate residences according to the circumstances under which they were built.

A third issue is how to provide the airport with a continuing incentive for noise reduction. Even after treatment, further noise reduction may be desirable, where possible, because in most cases treatment does not eliminate annoyance. If a single criterion for treatment is adopted, the airport would have no further incentives to reduce noise after the eligible affected residences have been treated.

Finally, the criteria have to allow for priorities in treatment. Soundproofing and relocation costs are among the most expensive noise mitigation measures (*1*). It is thus probable that many airports would not have the resources to soundproof or compensate all the residents in areas considered unacceptable (usually above 65 L_{dn}). There would be a need for staggering the expenses according to the severity of the problem and the resources available for noise mitigation.

THE BEN-GURION AIRPORT EXPERIENCE

Ben-Gurion Airport, Israel's main international airport, recently adopted this approach. The airport is located at the center of the country, surrounded by both urban and rural communities. It is near major transportation arteries, and is thus expected to remain Israel's main civilian airport in the future. Currently it has two intersecting runways. To allow the airport to fulfill its role in the future, a third runway was proposed. Discussions regarding it began in the late 1970s as part of a National Masterplan for airports. Communities under the approach to the proposed runway opposed it vigorously. By 1984 discussions reached a deadlock. To break out of the deadlock, the National Planning Board established an ad-hoc committee, headed by the Environmental Protection Service, to propose a noise abatement plan. A number of runway use patterns were discussed, including an "open V" pattern and a "noise sharing" formula. No agreement was reached regarding the best runway use patterns or a noise exposure map. Finally a "flexible plan" was adopted whereby the Airport Authority would not be limited as to the runway use pattern, but would have to treat residences where monitored noise exceeded certain levels. In addition, a noise zone and accompanying building limitations were agreed upon.

The criteria for treatment have three tiers. Immediate treatment is prescribed when noise exceeds 72 L_{dn}. If the measured noise in any year exceeded 70 L_{dn}, but was below 72 L_{dn}, treatment was required unless the airport managed to reduce the noise to levels below 68 L_{dn} for the succeeding 5 years (that is, if the noise exceeds 68 L_{dn} in any one of the following 5 years treatment would be required). In areas exposed to monitored noise levels between 68 L_{dn} and 70 L_{dn}, treatment would be required unless noise is reduced to levels below 68 L_{dn} within 5 years. This staggering of treatment requirements assures that the airport will have a continuing incentive to operate in a noise-sensitive manner. It also assures that the priorities for noise treatment will be based on noise exposure. Thus the residents subject to the highest noise exposure levels will be treated first. Furthermore, the 5-year interval between the time a residence is exposed to noise levels between 68 L_{dn} and 70 L_{dn} and the time the airport is required to treat it allows long-term improvements in noise emissions at the source to reduce the noise at the margins, thus saving costs.

The L_{dn} measurement used in these provisions is based on the noisiest 6 months of a year. Thus a full year of monitoring is required before treatment can be mandated. This should prevent aberrant patterns from unduly influencing the noise exposure map on which treatment decisions are made. The problem with this approach is that no account is taken of peak noise levels.

In addition a noise exposure map will be prepared, as a base for noise-related zoning. This map will be based on the Airport Authority's 5-year forecasts. Because exact future runway use patterns are unknown, the estimates for runway use will be weighted by 2.5 per runway. The noise contours thus will be clearly excessive, ensuring that residences will not encroach on areas that may be subject to high noise levels in the future. This high weighting is made possible by the high degree of government control over land in Israel. Most of the lands affected by noise from Ben-Gurion Airport are owned by the Israel Land Authority, a government entity. Consequently, the excessive building limitations do not require almost any compensation.

The noise zone is divided into four noise exposure areas. Between 60 and 65 L_{dn} all activities will be permitted. However, noise-sensitive uses will be required to be soundproofed at the developer's expense. Between 65 and 75 L_{dn} no new residential development will be approved. Improvements of existing residences will be allowed only with soundproofing. No sensitive activities will be allowed if levels exceed 75 L_{dn}. Nonsensitive activities, such as industry, would be allowed only with noise treatment. Variances from these regulations can be approved only by a special committee that will determine the conditions, if any, under which such variances may be granted.

These provisions will ensure that the airport will not be forced to treat any new developments. The inefficiency caused by residential encroachment is thus avoided.

CONCLUSIONS

This paper suggests an approach to airport noise mitigation based on current noise maps. By ensuring that noise abatement expenditures are a function of actual exposure rather than forecasted exposure, this approach provides a more cost-effective abatement strategy than current policies, which base receptor-oriented mitigation measures on forecasted noise exposure maps. This paper has shown such forecasts to be inherently uncertain. By relating airport actions to noise abatement expenditures, this approach also provides airports with an economic incentive to determine runway use patterns and operating procedures so as to minimize noise exposure. Because this incentive system is based on costs of noise mitigation, it may be more equitable than an incentive system based on the cost of litigation.

A number of practical issues have to be addressed before such an approach can be implemented. They include the determination of the time span over which noise modeling and measurements have to be conducted before action is undertaken; the relationship with noise-based zoning; the determination of priorities in treating residences exposed to noise levels considered unacceptable; and the provision of continuing incentives for airports to limit noise exposure.

At Ben-Gurion Airport in Israel, where such an approach has been adopted, a number of measures are used to address these issues. Multitiered criteria for treating residences provide both a measure to determine treatment priorities and a continuing incentive for airports to operate in a noise-sensitive manner. Only the residences affected by the highest levels of noise will be treated immediately. Residences in lower tiers will be treated only if noise is not reduced over a specified period of time. The time span of noise measurements should be approximately a year to prevent aberrant patterns from unduly affecting treatment decisions. Some account, however, should be taken also for peak noises. Zoning is based on forecasted noise maps. Variations from such zoning should be conditioned on soundproofing at the developer's expense.

Both this approach and the often suggested noise fees may improve noise abatement efficiency. This approach, however, may be easier to implement because it does not require estimating damage functions or future abatement costs. By improving efficiency, it enhances the competitive position of the airport. Furthermore, it shifts the focus of public debate from the assumptions underlying the noise exposure map to the criteria for noise abatement action, reducing community opposition to much-needed infrastructure improvements. This approach thus may hold some promise also for airports in the United States.

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Procedures For Evaluating Planned Development During The Noise Study Process

Jeffrey Force and Steven H. Hochman

The Federal Highway Administration's *Procedures for Abatement of Highway Traffic Noise and Construction Noise* requires that the New Jersey Department of Transportation (NJDOT) Bureau of Environmental Analysis (BEA) analyze expected noise impacts and abatement measures for undeveloped lands for which development is planned, designed, and programmed. To satisfy federal requirements to evaluate undeveloped land on which development is planned, while also minimizing disruptions in the roadway design process, a procedure was initiated to maintain thorough, early, and periodic coordination with affected municipalities during the noise study process. This procedure includes the identification of proposed residential developments during the preparation of the Final Noise Study (FNS) and before completion of roadway construction. Generally, early detection of proposed residential developments eliminates problems for NJDOT-Design Units and the NJDOT-BEA Noise Group caused by the recommendation of barriers for previously unknown housing developments after approval of the FNS. Detecting proposed residential developments late in the design study phase could possibly lead to delays in the approval of the FNS or to a significant redesign of the project.

The FHWA Federal Highway Program Manual, Volume 7, Chapter 7, Section 3 (FHPM 7-7-3) *Procedures for Abatement of Highway Traffic Noise and Construction Noise*, requires that the New Jersey Department of Transportation (NJDOT) Bureau of Environmental Analysis (BEA) analyze expected noise impacts and abatement measures for undeveloped lands adjacent to proposed roadway improvements on which development is planned.

Specifically, FHPM 7-7-3 says the following:

> "The traffic noise analysis shall include the following for each alternative under detailed study:
> 1) identification of existing activities, developed lands, and undeveloped lands for which development is planned, designed and programmed, which may be affected by noise from the highway
> 2) examination and evaluation of alternative noise abatement measures for reducing or eliminating the noise impacts."

The FHPM 7-7-3 also states:

> "The plans and specifications will not be approved by the FHWA unless those noise abatement measures which are reasonable and feasible are incorporated into the plans and specifications to reduce or eliminate the noise impacts on existing activities, developed lands or undeveloped lands for which development is planned, designed and programmed."

New Jersey Department of Transportation, Bureau of Environmental Analysis, 1035 Parkway Avenue CN 600, E & O Building, 4th Floor, Trenton, N.J. 08625.

This paper provides a detailed discussion of the need for New Jersey to implement the policy statement in FHPM 7-7-3 regarding impacts on undeveloped lands for which developments are "planned, designed and programmed." Also discussed are the procedures set forth to evaluate undeveloped lands adjacent to proposed roadway improvements on which development is planned. Finally, the effectiveness and limitations associated with the procedures will be examined.

IMPLEMENTATION OF PROCEDURES TO EVALUATE UNDEVELOPED LAND DURING THE NOISE STUDY PROCESS

The procedures to evaluate undeveloped land during the noise study process were developed to maintain thorough, early, and periodic coordination with affected municipalities to identify proposed residential developments early in the noise study process. Generally, early detection of proposed residential developments eliminates problems for Design Units and the BEA Noise Group caused by the recommendation of barriers for previously unknown housing developments after the approval of the Final Noise Study (FNS). Detection of proposed residential developments late in the design study phase could possibly lead to a delay in the approval of the FNS or to a significant redesign of the project.

One such example of the detection of a proposed residential development late in the design process is West Park Estates in Ocean Township, Monmouth County, New Jersey. West Park Estates is a 495-unit townhouse development in which 75 units would be affected by the proposed extension of Rt.NJ 18. The Noise Group did not detect this proposed residential development until after a public meeting with Ocean Township was held in October 1986. The purpose of the public meeting was to recommend noise abatement to the mayor and council and request any necessary easements for developments previously detected. As a result of this late detection, submission of the FNS was delayed (*1*). The contract modification requesting the consultant to look at noise mitigation for West Park Estates, the preparation of the noise mitigation report, and the review by the BEA Noise Group all delayed the completion of the FNS by approximately 1 year.

Also related to the need for thorough, early and periodic coordination with affected municipalities is the dynamic of development presently occurring in New Jersey. This growth is exemplified by the increase in population and the number of building permits authorized between 1980 and 1986 (*2, 3*).

The State of New Jersey experienced a population increase of 254,989 persons (3.5 percent). This increase coincided with the authorization of 257,759 dwelling units during the same time period (see Figure 1).

An increase in the authorization of building permits is also apparent in municipalities where transportation improvements are proposed. The rapid development in these municipalities has prompted the BEA-Noise Group to investigate possible noise mitigation measures to reduce impacts resulting from these transportation improvement projects. A few municipalities undergoing rapid residential growth (authorized building permits) between 1980 and 1986 include: Mt. Laurel Township, Burlington County (+74.0 percent), Bernards Township, Somerset County (+68.0 percent), South Brunswick Township, Middlesex County (+55.0 percent) and Tinton Falls Borough, Monmouth County (+51.0 percent) (see Figure 1).

Growth in New Jersey can be attributed to a natural population increase, net positive migration, transformation from a predominantly blue-collar state to an office-employment, service-oriented, high-technology state, and an improved transportation network.

1. Natural population increase. Between 1980 and 1986 there was a net positive population increase (births exceeding deaths) of 196,000 persons.
2. Net positive migration. Spillover growth zones are encountered within New Jersey. The Meadowlands in the north of the state and the Cherry Hill area to the south share this characteristic because of the influence of New York and Philadelphia, respectively. They provide land, relatively lower tax rates, and most important, excellent highway access.
3. Transformation to an office-employment, service-oriented, high-technology state. New Jersey's population has shifted from a highly centralized industrial society to a dispersed, exurban post-industrial era.
4. Improved transportation network. These changes in New Jersey are largely the result of national highway development, and particularly, the development of circumferential highways (*4*). The rise of the regional highway system with major intersections creates a ring of industrial and commercial development in the metropolitan areas structured on the new highways. Major highway development in New Jersey occurred late and is a direct cause of the state's lack of vitality in the 1970s. With the new matrix of transportation set in place, substantial growth in New Jersey is anticipated. This growth is expected to occur in various growth corridors throughout the state (*5*). Many of these parallel highway corridors include Rt.I-287 (Edison Township through Morristown); Rt.I-78 (from Berkeley Heights in Union County to Clinton Township in Hunterdon County); and Rt.I-80/280 Garden State Parkway nexus (from Parsippany-Troy Hills to Livingston and Saddle Brook).

MUNICIPAL LAND USE LAW OF NJ (MLUL) AND ITS RELATIONSHIP TO FHPM 7-7-3

The MLUL (Chapter 291, PL 1975) was the culmination of a more than decade-long effort to revise and streamline the unintegrated sections of law dealing with the various aspects of land use regulation—planning, zoning, and subdivision control in the State of New Jersey (*6*).

A few goals of the act are to

- Encourage municipal action to guide the appropriate use or development of all lands in this state, in a manner that will promote the public health, safety, morals, and general welfare,
- Ensure that the development of individual municipalities does not conflict with the development and general welfare of neighboring municipalities, the county, and the state as a whole,
- Promote the establishment of appropriate population densities and concentrations that will contribute to the well-being of persons, neighborhoods, communities, and regions and preservation of the environment,
- Promote the conservation of open space and valuable natural resources and prevent urban sprawl and degradation of the environment through improper use of land, and
- Encourage coordination of the various public and private procedures and activities shaping land development with a view of lessening the cost of such development and to the more efficient use of land.

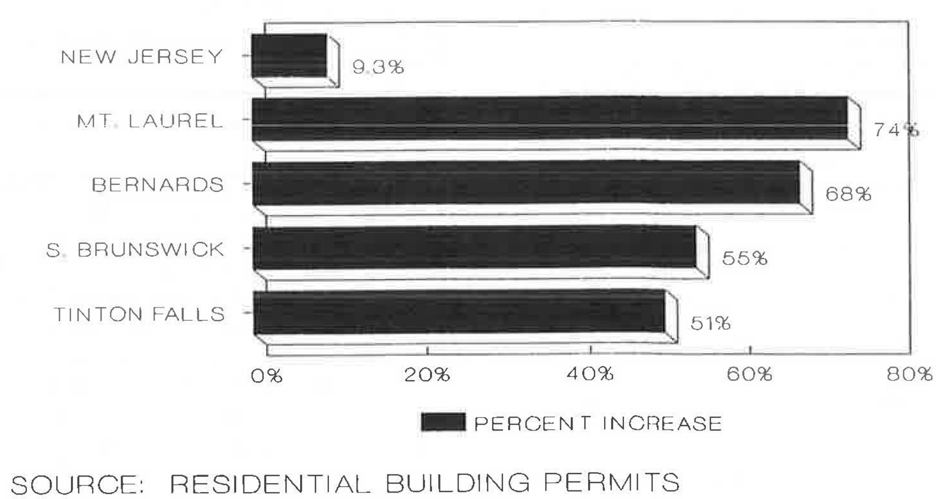

FIGURE 1 Growth in housing 1980–1986.

The MLUL has strengthened the role of municipal planning to ensure the prudent use of land and the protection of the environment. This law also provides municipal planning boards with the power to review and approve site plan or subdivision applications, or both.

Contained within the MLUL are the procedures for subdivision and site plan review and approval. A subdivision is the division of a lot, tract, or parcel of land into two or more lots, tracts, parcels, or other divisions of land for sale or development (e.g., residential single-family subdivisions containing individual lots). A site plan is a development of one or more lots (e.g., townhouse, apartment complexes, commercial, and industrial development).

The process involves three stages of approval, including: (a) Preapplication Sketch Plat-Concept Review, (b) Preliminary Plat Approval, and (c) Final Plat Approval. Below is a brief description of each stage of approval and any time limits associated with them.

Preapplication Sketch Plat Stage

This is the initial plan for the development of a parcel of land. Although sketch plats are not specifically discussed in the act, many municipal planning boards will request them.

Notable information required for this stage includes:

1. Survey of the site on which the proposed development is proposed, with dimensions.
2. Significant horticultural or physical site characteristics, including streams, stands of trees, swampy or high water table areas, ravines, rocks, and so forth.
3. Location and use of existing structures on the site and on adjacent property within 200 ft of boundaries, with dimensions.
4. Existing and proposed vehicular and pedestrian circulation systems on the site including streets, parking areas, driveways, walks, and so on, with street names and dimensions.
5. Topography of the site (where slope of site is less than 5 percent use 2-ft contours, where greater use 10-ft intervals).

Preliminary Plat or Plan Stage (Site Plan or Major Subdivision, three or more lots)

This is the first official stage of approval and contains more detailed information. Preliminary approval freezes the general terms and conditions for a 3-year period during which the applicant may file for final approval. The applicant may submit all or part of the preliminary plan for final approval within that time frame; however, an extension of up to 2 years may be granted.

Information required for this stage includes everything required at the preapplication stage plus information on all proposed setbacks.

Final Plat Approval (Site Plan or Major Subdivision)

The final stage should almost be automatic, provided that the applicant has made the necessary changes required under preliminary approval. No changes in zoning could occur for a period of 2 years after the date of final approval, as long as the applicant has recorded the plan within the time period provided in the local ordinance. An applicant may be granted a 1-year extension not to exceed three extensions prior to recording; or, as a condition of final plat approval, the planning board shall require the furnishing of a performance and maintenance guarantee for improvements, including streets, grading, paving, curbs, sidewalks, utilities, and so forth.

The final plat map should contain the following information: block and lot numbers, municipal boundary lines, natural and artificial watercourses, streams, shorelines, water boundaries and encroachment lines, monuments, name of map, municipality and county, date of survey, and so forth.

The MLUL does not address or regulate the events that occur following approval and recording of the final plat.

Two types of development approvals need to be considered:

1. Site Plan. The plan would include lot and buildings (e.g., apartments and some townhouse developments).
2. Subdivision Plat. If the subdivider is also the builder, the plan would include lots and buildings (e.g., single-family and some townhouse developments); if the subdivider is not the builder, the plan would show lots without buildings.

A development that is "planned, designed and programmed," as noted in FHPM 7-7-3, would appear to be equivalent to preliminary site plan/subdivision plat approval because a developer has expended much time and money in developing plans for this stage of municipal approval. Also, as stated previously, final plat approval is almost automatic pending resolution of preliminary plan review comments.

In some cases, however, the construction of houses may not occur immediately. In subdivisions with a residential cluster of less than 50 acres, or a conventional subdivision of less than 150 acres, no changes in zoning could occur for a 2-year period following final approval. Therefore, it is assumed that the developer would act to construct before the 2 years expire. However, on larger subdivisions, the municipality may grant rights longer than 2 years.

With regard to a subdivider who is not the builder, construction of homes may not occur for several years following final subdivision plat approval.

The BEA-Socioeconomic Group recently completed a survey to determine the typical time frame for a proposed development to advance from the preapplication sketch plat stage, through the preliminary site plan/subdivision approval stage to the final site plan/subdivision approval and then to construction. This survey was conducted for the 10 municipalities within the proposed Route NJ-92 corridor in central New Jersey (*7*). The Route NJ-92 project consists of constructing an approximately 13-mi-long interconnecting roadway link between US-206 north of Princeton and Route NJ-33 east of Hightstown. For the 10 municipalities surveyed, the average time for the development approval process to advance from the preapplication sketch plat approval to construction is 1 year (see Table 1). This time frame would be typical for a development with no unusual problems.

It is therefore critical to maintain close coordination with municipalities throughout the development of the FNS in order for developments receiving approvals to be addressed in the

TABLE 1 ROUTE NJ-92 CORRIDOR MUNICIPAL SURVEY: MUNICIPAL APPROVAL PROCESS

Municipality	Time from Preapplication to Construction
Cranbury Township	1 year
So. Brunswick Township	1 year
East Windsor Township	1 year
Franklin Township	1 year
Jamesburg Borough	2 months
Monroe Township	9–15 months
Plainsboro Township	8–10 months
West Windsor Township	8 months–1 year
Princeton Township	6–9 months
Montgomery Township	1 year

SOURCE: Municipal planning boards

FNS. A procedure needs to be developed to evaluate noise impacts on these developments.

PROCEDURES TO EVALUATE NOISE IMPACTS ON DEVELOPMENTS THAT ARE PLANNED, DESIGNED AND PROGRAMMED

Concern over maintaining close coordination with municipalities arose during discussions between the BEA and the Design Units. These discussions focused on when to address noise impacts on undeveloped lands where development is planned, in order to minimize disruption in the design process. The concern of the Design Units is that new barriers might be recommended (because of new housing developments) after FNS approval, when the location and heights of noise barriers are known. These new developments cause problems for Design because they require modifications in design plans.

As a result of these discussions, a procedure was developed by the Noise Task Force (composed of Design and Environmental personnel) to alleviate such problems. The Noise Task Force proposed that the FNS be completed before Phase II of the design process and any noise barriers recommended in this study be included in the Phase II plans. (Phase II is the completion of graphical development of the 30 scale design plans.) This proposal assumes that BEA receives the critical cross-sections, plan sheets and profiles needed for the preparation of the FNS by this phase.

Assuming completion of the FNS by Phase II, Design has determined that an 18-month time frame is needed to advance the project through final design (Phases II, III and IV) and to submit Plans, Specifications and Estimates (PS&E) to FHWA for approval. It is thus possible that a residential development could go from the preapplication stage to construction within this 18-month time frame (based on BEA's survey, the approximate time frame to go from the preapplication stage to construction is 1 year).

A mechanism is needed to ensure that, during and at the completion of the FNS (Phase II), coordination with the municipalities regarding new developments continues periodically up to the PS&E stage.

Following discussions between NJDOT and FHWA, a procedure was developed for meeting the federal mandate to evaluate noise impacts on developments that are "planned, designed, and programmed," while minimizing disruptions in the design process. The FHWA concurred with the BEA's prior assessment that preliminary site plan/subdivision approval would be equivalent to "planned, designed, and programmed" and that therefore those developments should be included in the proposed procedure (*8*).

The following procedure was proposed and implemented (*9*). Figure 2 also illustrates this process.

1. At the outset of the FNS, the BEA Socioeconomic Group will forward a letter to those municipalities affected by proposed highway improvement projects to determine which developments have received, or are about to receive, preliminary site plan/subdivision approval.
2. If a development receives such an approval and is affected by the proposed roadway improvement, the assumption would then be made that this development would go to construction within the next year (based on BEA's survey). This new development would then be evaluated on the basis of site plan/subdivision information available from the affected municipality, and the noise results and any barrier recommendations included in the FNS.
3. Just before the completion of the FNS, the BEA-Socioeconomic Group will check (via telephone call) with those municipalities to update the status of these and any new developments.
4. On completion of the FNS, a cover letter and a copy of the FNS would be sent to all municipalities affected by the proposed action. The FNS is sent to municipalities to inform them that future development located adjacent to the roadway may experience traffic noise if located within the areas delineated in the FNS.

The cover letter also indicates whether the use of abatement measures (noise barriers) would be cost-efficient and would effectively reduce noise. Finally, the cover letter requests that all municipalities affected by the proposed action exercise prudent planning regarding the approval of any new residential developments adjacent to the proposed improvements.

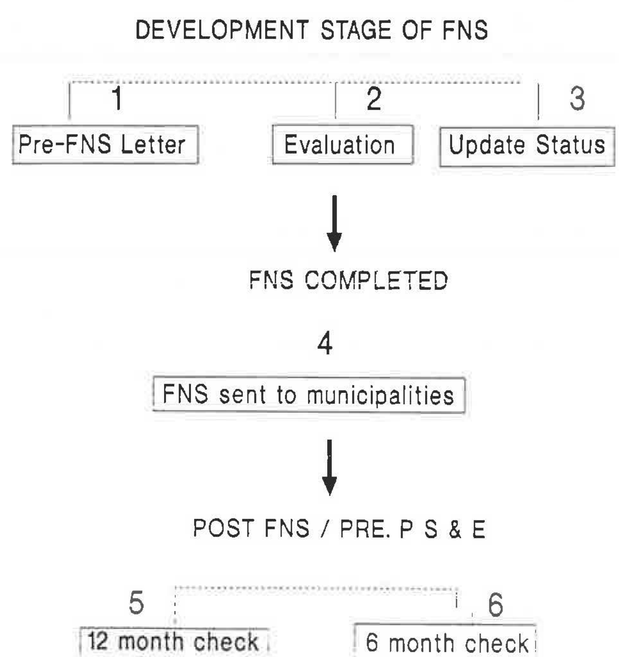

FIGURE 2 Procedures to evaluate planned developments.

These procedures are consistent with the goals of the Municipal Land Use Law "to encourage municipal action to guide the appropriate use or development of lands in this state, in a manner which will promote the public health, safety and general welfare." Municipalities, therefore, are given the responsibility to employ sound planning techniques through their subdivision and site plan review process. Approving residential developments adjacent to existing or proposed state highways without adequate buffers would not appear to be in the best interest of the public.

5. Twelve months before PS&E approval (approximately 6 months following FNS approval) the BEA-Socioeconomic Group would send another letter to the affected municipalities enquiring whether any developments have received preliminary or final site plan/subdivision approval. If such approval has been granted to a development, the BEA-Noise Group would begin a noise analysis, and any mitigation measures would have to be incorporated into the project plans before PS&E approval by FHWA.

6. A similar letter would be sent to the affected municipalities 6 months before PS&E; if needed, appropriate noise analysis and mitigation measures would need to be analyzed before PS&E approval. This 6-month check would be the final check by NJDOT on the status of proposed developments before PS&E approval by FHWA.

Throughout this period, extending from before the completion of the FNS to PS&E approval, the FHWA and the BEA-Noise Group would be kept updated with the information obtained from the affected municipalities through the use of the *Residential Development Check for Final Noise Studies Chart* prepared by the BEA-Socioeconomic Group (*10*) (see Figure 3.) This chart contains the status of all municipal correspondence regarding residential development checks for those projects requiring an FNS. It is updated monthly or as needed.

A TYPICAL PROJECT

PROJECT	LIMITS	MUNI./CO.
Rt. NJ 24 Sec. 9E, 10H	Rt. I-287 to Columbia Tpk.	Hanover, Florham Pk. Morris Twp. Morris Co.
LAND USE	MILESTONES	PRE. FNS
2/87	BE - C FNS - 5/89 PH2 - C PH3 - 1/89 PH4 - 3/89	Notification 9/87 5/88 Replies Hanover 10/87, 5/88 Florham Pk. 12/87, 5/88 Morris 12/87, 5/88
POST FNS	PRE. P S & E	

FIGURE 3 Residential check for final noise studies.

EFFECTIVENESS AND LIMITATIONS ASSOCIATED WITH THE PROCEDURES TO EVALUATE NOISE IMPACTS ON DEVELOPMENTS

Generally, the procedures implemented to detect proposed residential developments early in the design study phase have worked very well. The periodic checks with municipalities affected by proposed highway improvements have detected numerous developments, unknown previously to the NJDOT, that are in the early planning stages and that will require noise-mitigation assessments. It is this type of early detection that minimizes disruptions in the design process and prevents delays in and subsequent addendums to the FNS.

Limitations to implementing these procedures also exist, however. Many municipalities, for example, lack adequate staff and reply late or do not reply at all. Many municipal replies lack clear and concise information and do not contain all of the information requested, such as plans showing location of proposed buildings in relation to the proposed roadway improvements. Therefore, subsequent checks are required. Finally, it is often difficult to contact knowledgeable municipal officials when conducting periodic checks.

CONCLUSIONS

This paper has addressed the issue, "How does the NJDOT satisfy the federal requirement to evaluate undeveloped land on which development is planned while also minimizing disruptions in the roadway design process?"

In addressing this question, the state's growth trends and land use powers were researched. New Jersey has undergone tremendous residential growth in certain areas, and a need existed to coordinate effectively with municipalities that have the power to approve development.

Also, discussions were held with involved FHWA and NJDOT personnel to arrive at a plan that would be compatible with both the federal program and NJDOT Design procedures. During these discussions it was determined that residential developments receiving preliminary site plan/subdivision approval fall within the federal mandate of "planned, designed and programmed" and therefore cannot be ignored in the noise study process.

The procedure for evaluating planned development during the noise study process is a workable and concise plan. It implements the federal requirement by maintaining close and continuous coordination with municipalities to track new developments. As a result, delays to the design process because of new noise wall analysis and design are minimized.

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Automated Light Rail Transit (ALRT) in Vancouver, Canada: Measured and Perceived Noise Impacts

V. SETTY PENDAKUR AND HUGH MCLEAN

This paper analyzes the wayside noise impact of the Automated Light Rail Transit (ALRT) in the Broadway Station and Nanaimo Station areas of Vancouver, Canada. The research objective was twofold: to establish a relationship between noise levels and the distance to the ALRT guideway, and to relate residents' noise perceptions to the measured noise. In April 1986, noise measurements and a survey of residents' perceptions were undertaken by the School of Community and Regional Planning, University of British Columbia. Using this base data, the 24-hr L_{eq} was calculated. The analysis indicates that the relationship between noise and distance is semilogarithmic. An L_{eq} of 55 dB or more, after adjustments to the 24-hr L_{eq} based on criteria for previous community exposure to ALRT noise and background noise in the neighborhood, defines the zone of high impact. The distance from the ALRT guideway at which noise levels are unacceptable ranges from 20 to 200 ft. The Vancouver ALRT system was planned and built on the basis that only those properties within the ALRT right of way were to be acquired and noise impacts were not important. The experience since 1986 and this research indicate that noise impacts are important and should be mitigated. It is possible to establish measured zones of high impact. Planning goals must necessarily include the preservation of environmental quality. Prevention and mitigation of negative impacts must be part of the system's planning.

Vancouver is Canada's third largest metropolitan area, with 14 municipalities and a total population of 1.4 million in 1986. As early as 1970, rapid transit was promoted as an effective solution to transportation problems (*1*). The Greater Vancouver Regional District (GVRD) and the City of Vancouver produced plans for rapid transit systems with appropriate technology over the following 12 years, but neither group had the legal authority, taxation powers, or the finances to build a regional rapid transit system (*2,3,4*).

The turning point was 1982, when the provincial government announced that Vancouver would be the host city for a 1986 World's Fair with "TRANSPORTATION" as its theme. The fair, at first called "Transpo '86," was later named "Expo '86." In conjunction with Expo '86, it was decided to build a fully automated and elevated light rail transit system (ALRT). The planning, design and construction of the ALRT system was subsequently taken out of the hands of local/regional authorities and became the sole responsibility of a provincial crown corporation/agency called B.C. Transit. This agency is now responsible for all public transit in British Columbia. The system, as built, is shown in Figure 1. It is underground within the central business district, and the remainder is generally on an elevated guideway, with some segments at ground level or in-cut.

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STUDY AREA

The study covers the Broadway Station and the Nanaimo Station areas, as shown in Figure 2. In the vicinity of the Broadway Station is a mix of apartments, duplexes and single-family residences, with commercial activity along Broadway and Commercial Drive. South and east along the ALRT line toward the Nanaimo Station, the neighborhood consists primarily of single-family dwellings.

The decision by B.C. Transit, in 1982, to construct an elevated transit guideway parallel to Commercial Drive and through a residential neighborhood sparked local protest and controversy. B.C. Transit contended that this was the only practical route and that the suggested alternatives were uneconomical. Local residents and the city of Vancouver demanded that a cut-and-cover tunnel be constructed under Commercial Drive to avoid the demolition of homes and numerous other negative community impacts including noise (*5*). The additional $14 million required for a tunnel, however, was not acceptable to B.C. Transit, and construction began in early 1984 without local approval and amid much controversy. The ALRT system was in full operation by January 1986, in time for Expo '86, which opened in May 1986.

MEASURED AND PERCEIVED NOISE IMPACTS

Research Goals

The research goals were to calculate the 24-hr L_{eq} based on wayside ALRT noise and ambient background noise levels, to establish a relationship between ALRT noise and distance from the guideway, to delineate zones of high and low impact, and to analyze residents' perceptions of noise based on these zones of impact.

The zone of high impact is defined as the area in which ALRT outdoor noise levels are unacceptable. Canada Mortgage and Housing Corporation (CMHC) guidelines specify a

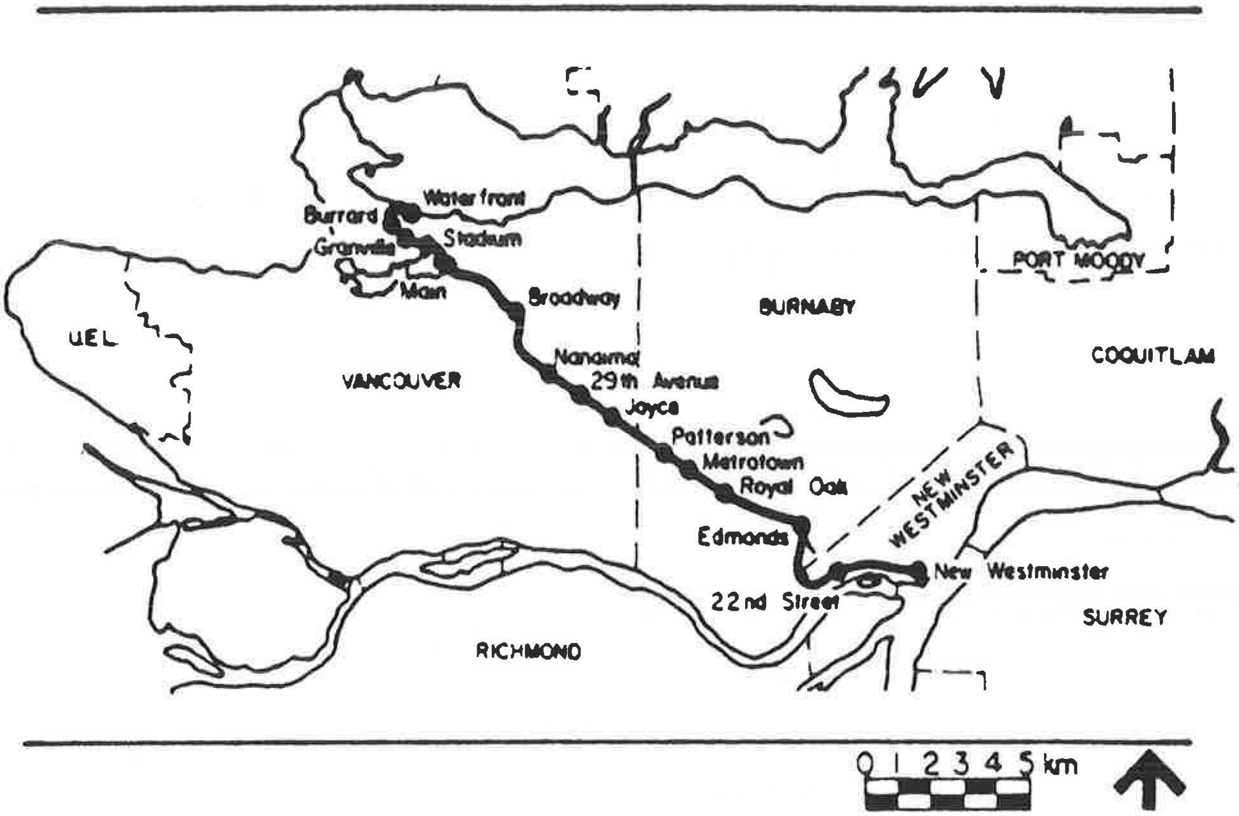


FIGURE 1 Regional ALRT route.

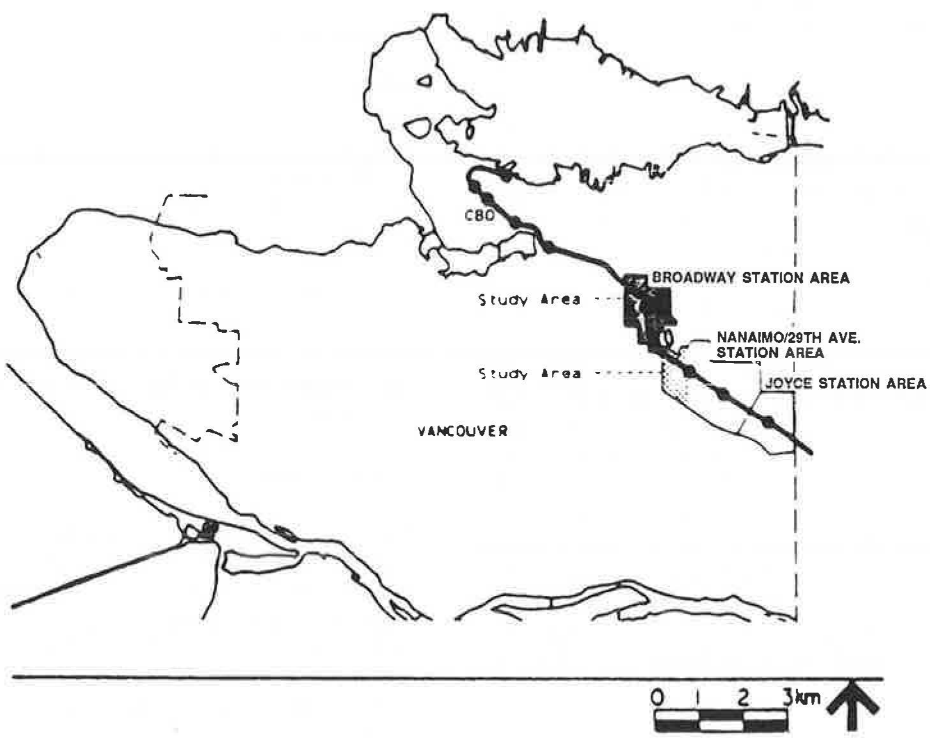


FIGURE 2 Study area: Broadway Station area and Nanaimo Station area west of Nanaimo Street.

24-hr L_{eq} of 55 dB or more as unacceptable in a residential area (*6*). The zone of low impact is the remainder of the study area, in which the 24-hr L_{eq} was less than 55 dB.

In order to relate noise levels to perceptions, an adjustment was made to the L_{eq} on the basis of U.S. Environmental Protection Agency (EPA) criteria for previous community exposure and noise levels measured in absence of the intruding noise (*7*). This adjustment applies only to relating the measured noise to perceptions. It was not used in the analysis of the relationship between noise and distance.

The EPA adjustments applicable to the study area were +5 dB for areas with no prior experience with intruding noise, and a correction for outdoor noise levels in the absence of intruding noise: zero dB for an urban residential community not adjacent to heavily traveled roads, or −5 dB for a noisy urban community near relatively busy roads (*7*). It is recognized that EPA adjustments apply to L_{dn} measurements. However, there is only a 3-dB difference between L_{eq} and L_{dn} if the ALRT system does not operate between 1.00 a.m. and 6.00 a.m., and at half the frequency between 6.00 a.m. and 7.00 a.m., and midnight and 1.00 a.m. (*8*).

Theoretical Aspects

Many factors contribute to the environmental quality of a neighborhood. Among the negative impacts of the ALRT, noise is the most easily identifiable and quantifiable. Often the benefits of improved accessibility on the regional scale take precedence over negative impacts imposed at the neighborhood level. The responsible authorities are all too often unaware of, or ignore, local impacts whether they be measured or perceived.

ALRT noise is generally produced by wheel-rail interaction and the electric motor. It can be intensified by wheel squeal around sharp curves and an elevated guideway, often the result of design constraints (*8,9,10*). Noise from elevated transit structures is also a function of train speed and length, distance from the track to the receiver, shielding, air and ground attenuation, structure type, and vehicle and track condition.

The perceived noise impact depends on whether residents consider the source as an intrusion, and whether their behavior is disrupted or enhanced (*11*). Responses to questions on rapid transit, in particular, depend on the noise magnitude as a function of frequency and time, socioeconomic conditions, the type of activity interfered with, past experiences and emotional associations with similar noises, individual sensitivity, and the type of question used in the survey (*12,13,14,15*).

Research Methods

The ALRT noise level forecasts for 1986 were obtained from a consultant's report and the municipality's expectations (*16,17*). The consultant study was done in 1983 and combined the measurements of ALRT pass-by noise taken at the ALRT Development Center in Kingston, Ontario; background noise was measured at three residential sites in the study area.

The East Vancouver Neighborhoods Study surveyed residents near the ALRT line during the ALRT construction, between May and August of 1984 (*18*). Residents were queried on the ALRT's influence on future neighborhood noise and neighborhood character. Socioeconomic characteristics were noted. No noise measurements, however, were taken in this study. The ALRT system was completed and became operational in January 1986.

In April 1986, noise measurements and a perception survey of residents were undertaken by the School of Community and Regional Planning at the University of British Columbia (V. S. Pendakur et al., "ALRT Noise Measurements in the Broadway Station Area," unpublished, 1987). Forty residential sites between the Broadway and Nanaimo Stations were chosen at random. The distance from the guideway for surveys and noise measurements varied from 20 to 320 ft (approximately one short block). The *A*-weighted noise measurements were divided into an indoor 15-min L_{eq}, peak indoor and outdoor levels, and ambient indoor and outdoor levels. For both the peak indoor and outdoor levels, four to six measurements were taken to obtain an average level.

Another set of measurements were taken on cross-streets at 50-ft intervals, up to 200 ft from the ALRT guideway. These measurements were of single-event maxima and ambient noise levels. They were taken at 76 sites. Together, outdoor noise measurements were performed at a total of 116 sites.

The L_{eq} values were measured with a Metrosonics Model 306/140 dB - 306 Metrologger, and single-event levels were measured with two Bruel and Kjaer Model 2206 Precision Sound Level Meters. Each device was calibrated to 92.5 dBA.

As a part of the perception survey, the residents were asked whether the ALRT noise could be heard indoors, and if so, in which rooms it could be heard. They were then asked if the noise affected their sleeping patterns. They were asked to rank ALRT noise with all other neighborhood noises, and to rate the overall noisiness of the neighborhood.

Analysis

All single-event noise measurements and the background noise were converted to 24-hr L_{eq} levels. This convention was based on the following formula (*8*):

$$L_{eq} = L_a + 10 \log (nl) - 49$$

where

n = number of trains per hour for the L_{eq} time period,
l = length of a train in meters, and
L_a = the maximum *A*-weighted sound level for train pass-by.

The background noise was converted to a 24-hr L_{eq} using a model developed by Barron and Associates (*19*). The model assumes that the noise levels are at maximum from 6 a.m. to 6 p.m., dropping from 6 p.m. to midnight and lowest from midnight to 6 a.m. Examples applicable to the study area are 60 dB, 54 dB and 48 dB for the three periods respectively.

The relationship of ALRT noise and distance from the guideway was computed by using regression analysis. Those sites where background noise contributes more to the 24-hr

L_{eq} than the ALRT pass-by noise are excluded, reducing the total number of sites from 116 to 93.

Environmental factors such as the height of the ALRT guideway, shielding and reflection of noise, and topography, each have an influence on the 24-hr L_{eq}. It is not within the scope of this study, however, to assess the relative significance of these factors. Similarly, other noise sources such as traffic are considered here as part of the background L_{eq}. The relative significance of each of these has not been studied here.

A zone of high impact is based on a 24-hr L_{eq} of 55 dBA or more. Adjustments were made to the 24-hr L_{eq} for previous community exposure and background noise for all 1986 noise measurements. The previous studies provide noise measurements and forecasts, but differ somewhat in the perception questionnaire. Therefore, they are analyzed separately and not combined with the 1986 measurements.

The two important perceptions from the 1984 East Vancouver Neighborhoods Study are the anticipated effect of the ALRT on neighborhood noise levels and neighborhood character. Residents were asked to rate the effect as better, no change or worse. These were analyzed together with a set of other perceptions, such as the factor liked best or least in the neighborhood, the anticipated changes in the area including traffic on local streets, and the quality of public transit service. The cross-tabulation procedure was used to obtain the association between nominal variables, and the nonparametric procedure calculated the Kendall Tau-b values for a bivariate analysis of ordinal variables.

Data from the 1986 Noise Perception Survey were coded on a weighted scale of 1 to 5 for statistical analysis. The three main categories were: Perceived Extent of ALRT Noise, Noisiness of the Neighbourhood, and Rank of ALRT Noise with Other Noise Sources. The coding system is shown in Table 1.

These perceptions were analyzed with the adjusted 24-hr L_{eq}. At 5 of the 40 residential sites, background noise was a greater contributor to the 24-hr L_{eq} than the ALRT pass-by. These sites were, therefore, excluded from the analysis of perceptions.

RESEARCH FINDINGS

The outdoor 24-hr L_{eq} at the 40 residential sites are shown in Table 2. Similar data for street level locations are shown in Table 2. The site locations in relation to the ALRT guideway are shown in Figures 3, 4, 5 and 6. Data in Tables 2 and 3, and in Figures 3 and 4 indicate that there are many sites in the study area where ALRT noise levels exceed acceptable CMHC standards.

Background noise, predominantly road traffic, contributes more to the 24-hr L_{eq} than the ALRT along three streets: East 11th Avenue, Victoria Drive and Nanaimo Street (see Figures 3 and 4). Virtually all the other figures show that noise decreases to varying degrees with greater distance from the ALRT guideway. The average L_{eq} at each of the 50-ft intervals are: 58 dB, 54 dB, 53 dB and 50 dB. This is similar to the 1983 forecasts (*16*).

Between the Broadway Station and Hull Street (Maps 3a and 3b) except for East 15th Avenue, the L_{eq} exceeds 55 dB up to 200 ft from the guideway. Along the west side of the guideway, the noise from and road traffic on Commercial Drive limits the impact of ALRT noise.

TABLE 1 PERCEPTION ANALYSIS: CODING SYSTEM

Category	Scale Original	Scale Recoded
Perceived extent of ALRT Noise		
Minimal/no impact	1	1
Noise heard only outside	2	
Heard in one room	3	2
Heard in > one room	4	3
Heard everywhere	5	4
Sleeping pattern affected	6	5
Noisiness of neighborhood		
Quiet	1	1
Fairly quiet	2	2
Moderately quiet	3	3
Noisy	4	4
Very Noisy	5	5
Rank of ALRT noise with other noise sources		
ALRT is noisiest	1	5
ALRT is second noisiest	2	4
ALRT is third noisiest	3	3
ALRT is fourth noisiest	4	2
ALRT is fifth noisiest	5	1

Between Hull Street and the Nanaimo Station, the impacts differ in intensity and distance. To the north of the guideway, ALRT noise exceeds 55 dB only at 50 ft, while at greater distances, the noise levels are acceptable. On this side, the topography drops significantly moving away from the guideway. To the south of the guideway, the noise levels exceed 55 dB up to 150 ft. This higher level may result from more open space and a gradual incline moving away from the guideway.

The regression analysis shows a marked correlation between noise and the log of distance ($r = -0.723$, $p < .0001$), with over half of the observed variance explained by the model ($r^2 = 0.523$). The 24-hr L_{eq} drops by 15 dB from 20 ft to 320 ft. The equation representing the complete study area is:

$$\text{Noise} = 79.99 - 12.45 \log(\text{Distance measured in ft}).$$

The scattergram is shown in Figure 5.

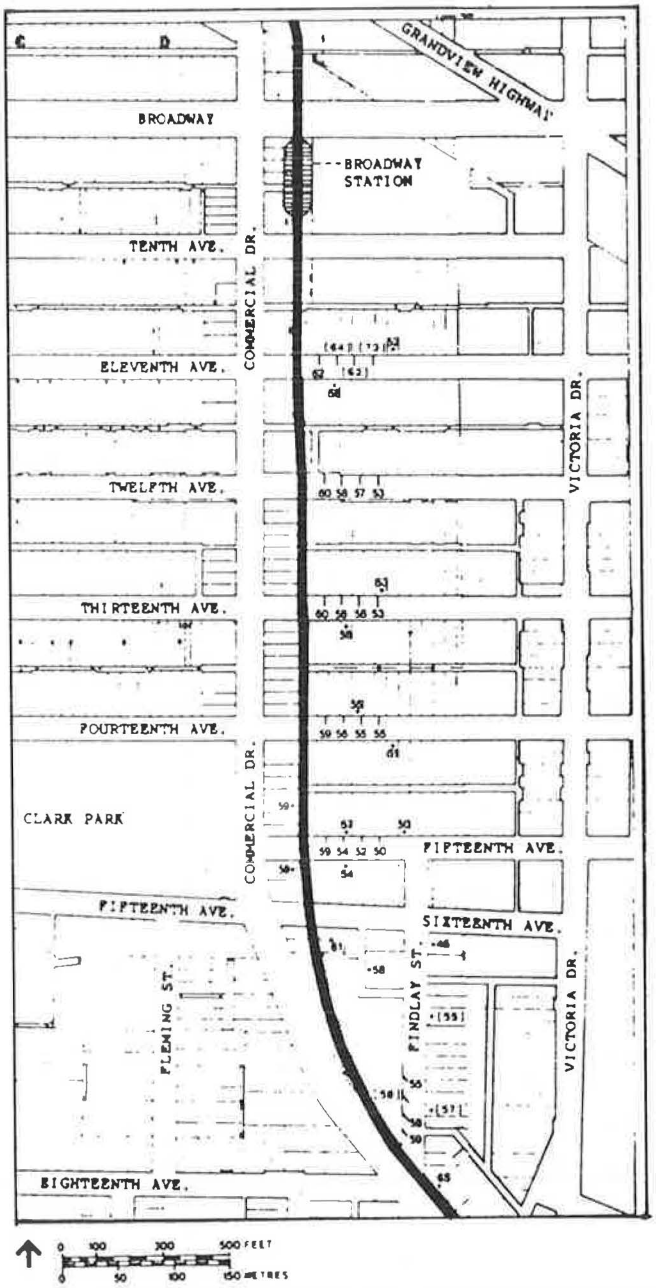
The distance from the guideway is divided into three segments, where the first segment is approximately less than two-thirds of the wheel track spacing, and the third segment is approximately more than two-thirds of the train length (*10*). This would divide the distance from the guideway at points of 26 ft and 92 ft. In the first and third segments, the noise represents a line source and in the middle segment, it resembles a point source (*10*).

The correlation and slope for the first segment is not computable because all the three points are at the same distance from the guideway. In the second segment, $r = -0.391$ with a significance of 0.02, and 15 percent of the variance is explained by the model ($r^2 = 0.152$). In the third segment, $r = -0.601$, with a significance of 0.0000, and 36 percent of the variance

TABLE 2 OUTDOOR 24-HOUR L_{eq} AT RESIDENTIAL SITES

	ALRT PASS-BY OUTDOOR dBA			BACKGROUND dBA		
SURVEY SITE	AVERAGE	PURE PASS-BY	24-HR L eq	SINGLE-EVENT	24-HOUR L eq	TOTAL 24-HOUR L eq
01	80.6	81	59	50.0	47	59
02	75.0	75	53	50.0	47	54
03	77.3	77	55	54.0	51	56
04	75.0	75	53	46.0	43	53
05	72.6	73	51	50.0	47	52
06	77.3	77	55	46.0	43	55
07	72.4	72	50	46.0	43	51
08	66.6	67	45	42.0	39	46
09	71.4	71	49	45.0	42	50
10	80.6	81	59	60.1	57	61
11	80.4	80	58	56.5	54	59
12	76.6	77	55	58.0	55	58
13	67.8	68	46	56.6	54	[55]
14	73.9	74	52	58.0	55	[57]
15	87.0	87	65	55.5	53	65
16	76.8	77	55	55.0	52	57
17	75.4	75	53	54.0	51	55
18	84.7	85	63	62.0	59	64
19	64.5	65	43	45.0	42	46
20	64.8	65	43	42.0	39	44
21	87.5	88	66	42.0	39	66
22	80.7	81	59	51.0	48	59
23	77.8	78	56	44.0	41	56
24	67.8	68	46	48.0	45	49
25	72.5	73	51	54.0	51	54
26	63.7	64	42	50.0	47	[48]
27	76.1	76	54	54.0	51	56
28	68.8	69	47	46.0	43	48
29	72.8	73	51	48.0	45	52
30	71.5	72	50	52.0	49	53
31	69.0	69	47	44.0	41	48
32	76.3	76	54	47.0	44	54
33	62.2	62	40	39.0	36	41
34	78.7	79	57	55.0	52	58
35	78.6	79	57	50.0	47	57
36	67.0	66	44	62.0	59	[59]
37	59.8	60	38	46.0	53	[44]
38	73.4	73	51	51.8	49	53
39	73.0	73	51	47.1	44	52
40	75.3	75	53	54.5	52	56

Source: Calculated from 1986 UBC Study
Note: Brackets [ ] indicate that the background noise level contributes more to the 24-hour L eq than the ALRT pass-by.



NOTE: 1. All noise levels are measured in dB(A). 2. Brackets indicate that background noise exceeds ALRT pass-by level. 3. *e* refers to noise measurements at residential sites.

FIGURE 3 Total 24-hr L_{eq}.

is explained ($r^2 = 0.361$). The null hypothesis of no difference between the two slopes (i.e., $B_1 - B_2 = 0$) was tested. The 95 percent confidence interval was calculated as $0.904 < B_1 - B_2 < 2.397$, resulting in rejection of the null hypothesis.

The study area is also divided into two sections: from the Broadway Station to Hull Street, and from Hull Street to the Nanaimo Station. For the former, there is a strong correlation ($r = -0.833, p <. 0001$), and over 69 percent of the observed variance is explained ($r^2 = 0.694$). For the latter, the correlation is significant ($r = -0.733$, $p < 0.0001$), but less of the observed variance is explained ($r^2 = 0.538$).

The adjusted 24-hr L_{eq} of 55 dB defines the zone of high impact (Figures 6 and 7). For calculating the adjusted 24-hr L_{eq} between the Broadway Station and Hull Street, no adjustment was made. The community had no prior experience with the noise, which justifies the addition of 5 dB to the L_{eq}; at the same time, this is a very noisy urban residential community which, under EPA criteria, would reduce the L_{eq} by 5 dB.

From Hull Street to the Nanaimo Station, 5 dB is added to the L_{eq}, because there was no prior exposure to the noise at that time; furthermore, it is an urban residential community not immediately adjacent to any arterial streets.

The nonparametric analysis of residents' perceptions shows that for the complete study area, as the ALRT noise increased, the residents tended to rate the neighborhood as noisy ($r = 0.3765$, Sig 0.002). Between these two variables, however, neither correlation was significant in the two zones. For the ALRT noise and the perceived extent of ALRT noise, none of the correlations was statistically significant. For the adjusted L_{eq} and ranking of ALRT noise with other sources, there is a pattern of ranking the ALRT as the first or second largest contributor to neighborhood noise, regardless of the adjusted 24-hr L_{eq}. This results in poor correlations for the study area as a whole, and in each zone of impact.

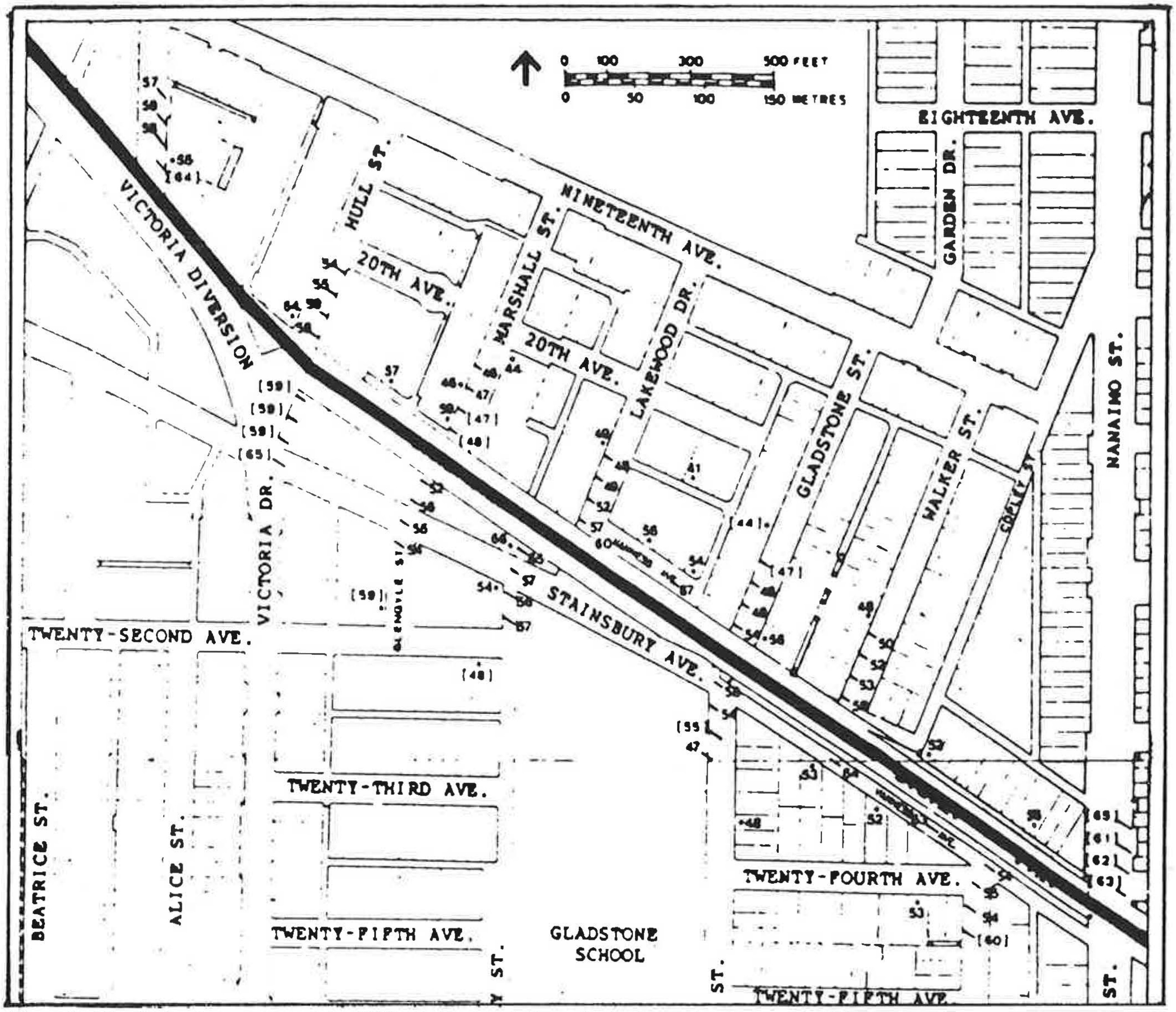
For the perceived extent of ALRT noise, in the zone of high impact, there is 1 case in 23 where the noise is heard only outside (58 dB), and 1 case where it is heard in only one room of the dwelling (56 dB). One case claimed that the noise was heard in more than one room at 71 dB. These three cases suggest a lack of emphasis on the impact. There are two cases at 55 dB where noise is claimed to affect sleeping patterns. Based on CMHC standards, these two cases suggest an exaggerated sensitivity on the part of the respondents. These responses are not consistent with measured noise impacts.

Of the 12 cases in the zone of low impact, 3 claim that the ALRT affects sleeping patterns at an L_{eq} of 50 dB, 51 dB, and 53 dB. One case at 51 dB, two cases at 53 dB and one case at 54 dB claim that the ALRT noise is heard everywhere in the residence. It appears that in this zone, these seven cases do not represent responses consistent with other studies. The location of these seven cases does not indicate that such a response is the result of a quiet location. Four of the seven cases are from the noisier area, between the Broadway Station and Hull Street.

For the analysis of the discrepancies between the two zones of impact, the variable "noisiness of the neighborhood" presents similar findings to those for the "perceived extent of ALRT noise." In the zone of high impact, the frequencies show that there are only 3 cases out of 23 where the noise impact is underrated by the respondent: at 57 dB there is one case claiming the neighborhood is "quiet," while at 58 dB and 61 dB, one case for each claims "some noises." The remainder of cases appear to be consistent with the measured noise impact based on CMHC standards.

In the zone of low impact, 5 cases out of 12 do not appear to be representative of the measured noise. At 46 dB and 49 dB, there is one case for each where the neighborhood is judged as "fairly noisy," and one case at 50 dB and two at 51 dB where the judgement is "noisy." These five cases may account for the poor Tau-b correlation in this zone.

The comparison between the two zones of impact indicates that there is a greater proportion of cases in the zone of low



NOTE: 1. All noise levels are measured in dB(A). 2. Brackets indicate that background noise exceeds ALRT pass-by level. 3. *e* refers to noise measurements at residential sites.

FIGURE 4 Total 24-hr L_{eq}.

impact where the perceptions are not representative of the adjusted 24-hr L_{eq}. The perceived noisiness of the neighborhood is a slightly more accurate indicator of the measured noise impact than the perceived extent of ALRT noise.

For the complete study area, those households with four or more occupants tend to claim that ALRT noise affects sleep. Also, those with four or more occupants and those having lived in the study area longer than 10 years rank the ALRT as one of the largest contributors of all sources. In the high-impact zone, those in single-family dwellings and those having resided in the area 2 years or more generally perceive that the ALRT noise affects sleep patterns. Those with four or more persons in the household tend to rank the ALRT as the greatest contributor. In the zone of low impact, those with a longer residency, at least 10 years, rank ALRT noise as the greatest contributor and evaluate the noisiness of the neighborhood as "noisy" or "very noisy."

The pre-ALRT perceptions measured in the 1984 East Vancouver Neighborhoods Study also reveal some variation between the two zones of impact. For the complete study area, 42.1 percent believed that the ALRT would have no effect on neighborhood noise levels, and 38.2 percent gave a negative outlook. In the zone of high impact, 48.5 percent were neutral, and 33.3 percent had a negative outlook. In the zone of low impact, 41.3 percent were neutral, 38.9 percent were negative, and 6.9 percent were positive in their outlook.

In the zone of high impact, there was no evident association between a negative outlook on the effect of the ALRT on

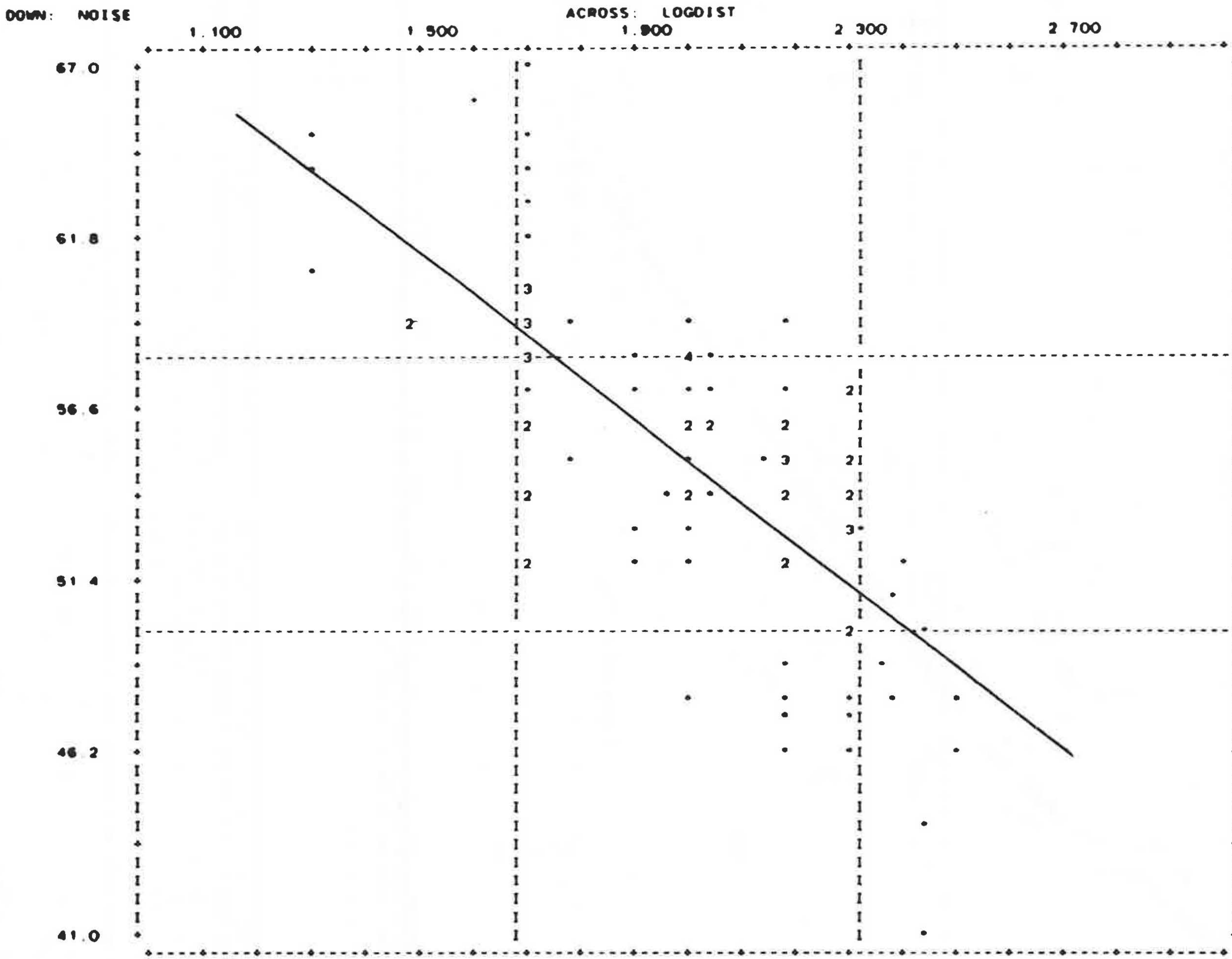


FIGURE 5 Scattergram: Noise (24-Hour L_{eq}) and log of distance.

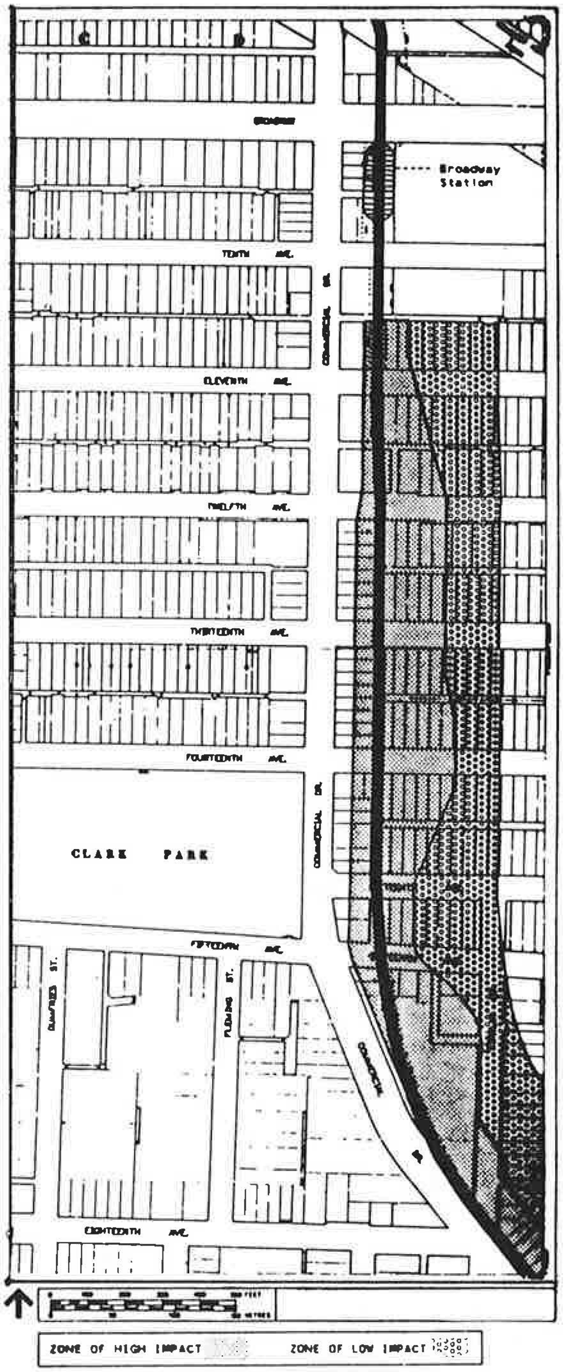


FIGURE 6 Zones of impact based on adjusted 24-hr L_{eq}.

neighborhood noise and one single factor liked or disliked in the neighborhood. In the zone of low impact, however, a negative attribute associated with a negative response to future ALRT noise was traffic noise (26 percent).

In the zone of low impact, those having a negative attitude toward the ALRT's effect on future neighborhood noise levels also had a negative outlook toward its effect on neighborhood character (0.2244, Sig .001). Furthermore, those anticipating higher noise levels noted a problem of noisy neighbours (0.1750, Sig .003).

For the complete study area, a neutral response tended to come from those frequently at home, such as homemakers, the retired and the unemployed, as well as from blue-collar workers. White-collar workers tended to have a negative response. A neutral response applied to age groups over 40 years, while a negative response was evident from the two youngest age groups, 16–29 and 30–40 years. In the zone of high impact, there was a tendency for those knowing more than five people on the block and those owning the residence to anticipate a negative effect from ALRT noise, while a neutral response was attributed to those not owning the residence. In the zone of low impact, those who have a white-collar job were more likely to anticipate higher noise levels, and those remaining at home tended to give a neutral response.

CONCLUSIONS

The research underlying this paper has been neither exhaustive nor covered all environmental factors. Nevertheless, the following conclusions can be drawn:

1. Vancouver's ALRT system produces noise levels that exceed the acceptable community environmental standards established by the CMHC (24-hr $L_{eq} > 55$ dBA).
2. In general, the ALRT noise levels decrease with distance from the ALRT guideway. The 24-hr L_{eq} decreases 15 dBA from 20 ft to 320 ft distance from the ALRT guideway.
3. Even though several factors influencing noise impact (guideway geometrics, housing structure differentials, socio-economic and demographic differentials of respondents) were not studied in detail, the analyses indicate that the relationship between ALRT noise and distance from the guideway in the study area is semilogarithmic. For this particular study, the relationship is:

$$\text{Noise} = 79.99 - 12.25 \log(\text{Distance in ft})$$

4. It is possible to define zones of high impact where the noise levels are expected to exceed community environmental standards.
5. Within the zones of high impact (24-hr $L_{eq} > 55$ dBA), the perceived noise levels are consistent with the measured noise levels.
6. Within the zones of low impact (24-hr $L_{eq} < 55$ dBA), the perceived noise levels are substantially higher than measured noise levels. This perception is more pronounced in larger households.

PLANNING IMPLICATIONS

Unlike the mandatory requirements in the United States regarding environmental impact statements, information dissemination and public participation, the transit authorities in British Columbia are not required to publish environmental impact statements. Furthermore, the B.C. Transit Act states that neither B.C. Transit nor the Province of British Columbia is legally obligated to compensate the residents, so long as their property was not acquired by expropriation or otherwise. In the case of Vancouver's ALRT, B.C. Transit decided that

TABLE 3 TOTAL 24-HOUR L_{eq} (DECIBELS)

STREET	DISTANCE FROM GUIDEWAY			
	50 FT. (15.5 M)	100 FT. (31.0 M)	150 FT. (46.5 M)	200 FT. (62.0 M)
E. 11th	62	[64]	[62]	[73]
E. 12th	60	58	57	53
E. 13th	60	58	56	53
E. 14th	59	56	55	55
E. 15th	59	54	52	50
FINDLAY	59	58	[58]	55
VICTORIA DR. N.	[64]	58	59	57
HULL	58	59	55	54
HULL-VICTORIA	[59]	[59]	[59]	[65]
MARSHALL	[48]	[47]	47	46
GLENGYLE	52	56	55	54
LAKEWOOD	57	52	49	48
SIDNEY	65	57	56	57
VANNESS East of Lakewood	60	--	--	--
VANNESS West of Gladstone	67	--	--	--
GLADSTONE N. of Guideway	54	48	48	[47]
GLADSTONE S. of Guideway	58	54	[55]	47
WALKER	58	53	52	50
VANNESS East of Gladstone	64	--	--	--
VANNESS West of Brant	63	--	--	--
BRANT	54	55	54	[60]
NANAIMO N. of Guideway	[63]	[62]	[61]	[65]

Source: Calculated from 1986 UBC Study
Note: Brackets [ ] indicate that background noise contributes more to the 24-hour L eq than the ALRT pass-by.

it will not acquire or expropriate any properties that are not within the right of way. Neither were any noise mitigation measures undertaken. Furthermore, "the B.C. Transit Act protects the government from claims of injurious affection arising from the transit systems" (*19*).

Some governmental agencies are recognizing the fact that negative environmental impacts have negative impacts on property values. The British Columbia Assessment Authority, which establishes the base values of real estate property for taxation purposes, decided in 1987 to reduce the property values within 300–600 feet of the elevated or at-grade guideway throughout the metropolitan area. These reductions ranged from 15 percent to 20 percent of the total value. The Ombudsman of British Columbia, appointed by the Legislature, is an independent guardian of the public trust. The ombudsman in a recent study of the negative environmental impacts of the ALRT has recommended that the government compensate affected property owners (*20*).

This research has established that there are zones of high impact adjacent to the ALRT guideway where noise levels exceed accepted community standards. Although further research is necessary to delineate clearly the extent of impact zones throughout the system area, proper mitigation measures appear to be warranted.

The extent of the high-impact zone depends upon geometrics, land use, community exposure to noise and the socioeconomic characteristics of the residents. In the low-impact zone where the noise perceptions are exaggerated, it is necessary to provide for an open transportation planning process in which citizens can learn, understand and appreciate the noise measurements and methods used.

These research findings can be used for forecasting the extent of the high-impact and low-impact noise zones. They must, of course, be modified by further research including a discriminant analysis of other geometric, operational, topographical factors and perception related variables. Successful

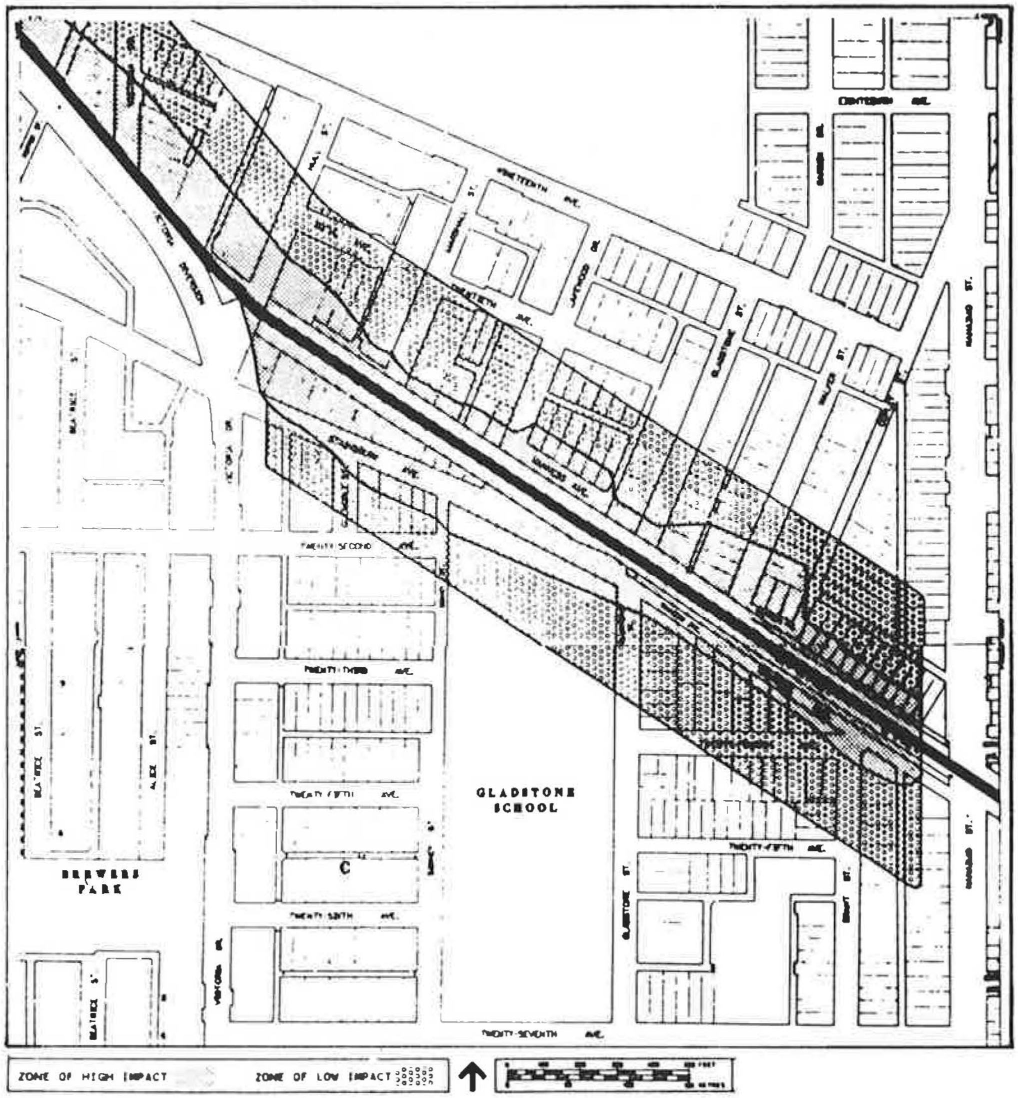


FIGURE 7 Zones of impact based on adjusted 24-hr L_{eq}.

transportation planning and implementation depend on the planner's understanding the citizens and their concerns, and respecting long-term environmental quality.

ACKNOWLEDGMENTS

Graduate students in urban transport planning at the University of British Columbia conducted the surveys and noise measurements in 1986; without their involvement this research would not have been undertaken. Assistance and valuable comments by Ken Barron of Barron and Associates, Nick Losito of the City of Vancouver, and Henry Hightower and Krishna Pendakur of the University of British Columbia are gratefully acknowledged.

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Noise Investigation of the Pennsylvania Turnpike Widening

JAMES J. SCHUSTER AND MICHAEL K. WONG

The existing four-lane Delaware River Extension of the Pennsylvania Turnpike reaching from Valley Forge to the Delaware River traverses the most developed region in the state. The net effect of growth over 30 years is congestion and traffic-generated noise. At present, the turnpike is a four-lane, controlled-access highway with 10-ft shoulders along its length and a 10-ft median with guide rail. The project described in this paper involves the installation of extensive noise wall barriers and the widening of the turnpike to six lanes. A total of 57 noise receptor points were analyzed. The 2006 design year L_{eq} noise level for the noisiest hour of each receptor was predicted by means of the calibrated STAMINA 2.0/OPTIMA computer program. This provided the individual noise contributions of the Pennsylvania Turnpike, various arterials and local roads, and the logarithmic addition of all roadway noise to provide a total noise level at each receptor site. An inspection of the data yielded the following: the predicted noise levels exceeded established noise abatement criteria at 16 sites, and noise mitigation in the form of noise barrier walls was required. The location, dimensions and cost of the barriers were determined along with the predicted reduction and noise levels. An after study was later completed that compared actual with predicted and existing noise levels. The decrease ranged from 2.9 dBA to 13.0 dBA.

The existing four-lane Delaware River Extension (I-276) of the Pennsylvania Turnpike reaching from Valley Forge to the Delaware River traverses the most developed region in the state. Since the opening of this section of the turnpike in 1954, heavy residential, commercial and office development has taken place along this corridor. The net effect of this growth is that congestion is common along this section of the turnpike.

The Pennsylvania Turnpike Commission completed the widening to six lanes of certain sections of the Pennsylvania Turnpike on land it already owned (*1*,*2*). The design constraint of no new right of way applied to all construction elements including noise barrier placement. The westernmost section is the subject of this report. The project site is located in Montgomery County between the communities of Cold Point and Fort Washington. Financing for the construction is from the tolls generated by the commission, which is not required to conform to the various design standards of the Pennsylvania Department of Transportation.

The turnpike was a four-lane, controlled-access highway with 10-ft (3.05-m) shoulders along its length and a 10-ft (3.05-m) median with guide rail. Widening of this section of the turnpike to six lanes with 12-ft (3.66-m) usable shoulders and a 10-ft (3.05-m) maximum, 4-ft (1.22-m) minimum median with concrete barrier along the center of the median would provide for the safe and efficient flow of traffic now and in the future, relieving the congestion problem.

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NOISE STUDY—BEFORE

Purpose

The purpose of this study is to investigate and describe existing and future noise levels on both the Pennsylvania Turnpike and local roads in the vicinity of the study section.

Under the scope of this study, ambient noise conditions are described, including recent noise measurements of the communities adjacent to the Pennsylvania Turnpike and various local roads. Noise impacts are analyzed for both the existing and predicted (design year 2006) conditions. From this analysis noise mitigation recommendations are developed. These recommendations are made after integration of geometric design with design optimization and value engineering, involvement of the community, and coordination with the design of adjacent sections.

Methodology

The existing noise results were obtained by field measurements and determination of representative levels by analogy with similar sites (*3*,*4*). Predicted noise results were obtained by computer modeling of traffic, geometry and site conditions. Prediction of the 2006 (the design year) noise levels that would result from the widening of the Pennsylvania Turnpike was made by means of a noise program based on the methods detailed in the Federal Highway Administration report, FHWA-RD-77-108, *FHWA Highway Traffic Noise Prediction Model: Highway Noise* (*5*). The FHWA's computer program, STAMINA 2.0 (an acronym for Standard Method in Noise Analysis, version 2.0), which is in concert with Federal-Aid Highway Program Manual, Volume 7, Chapter 7, Section 3 (FHPM 7-7-3) of the Federal Highway Administration, U.S. Department of Transportation, was run on an IBM Computer 3081 and included all necessary adjustments relating to distance, gradient, highway section characteristics, vertical height, flow conditions, ground and shielding effects, and height adjustments for receivers, autos and trucks (*6*,*7*).

Traffic

Turnpike traffic is the principal source of noise in the community. The existing peak hour one-directional traffic volume on this turnpike section is 3,060 vehicles distributed over two lanes. Field noise measurements and 24-hour truck classification counts indicated that the noisiest time period was between 3:00 p.m. and 5:00 p.m. and that the traffic during this time does not vary because of the consistent nature of the commuter work-to-home trip. Simultaneous recording of traffic and noise levels was, therefore, not considered necessary. This existing volume exceeds the Level of Service (LOS) C service volumes according to the *Highway Capacity Manual*, and indicates operation at an unacceptable peak hour level of service. At this volume, the turnpike was operating at LOS E because the volume to capacity (V/C) ratio was computed at 0.98 at LOS E. Therefore, the proposed widening to six lanes was needed to improve the level of service.

The peak hour one-directional traffic volume in 2006, the design year, is estimated to be 3,430 vehicles. Because this projected volume is less than the Level of Service C service volume, the proposed widening of this turnpike section to three lanes in each direction will provide an adequate Level of Service for the design year 2006 traffic conditions.

Predicted Noise Levels and Impacts

A total of 57 receptor points, including 18 monitoring sites, 25 analysis points and 14 supplementary analysis points were devised and identified.

The design year L_{eq} noise level of each receptor was predicted by means of the calibrated STAMINA 2.0 computer program. Calibration was achieved by comparing existing field noise measurements with predicted noise levels, using existing traffic and model input parameters. Tabular values for the noisiest hour yield the individual noise contributions of the Pennsylvania Turnpike, various arterials and local roads, and the logarithmic addition of all roadway noise to provide a total noise level at each receptor site. An inspection of the data yields the following observations:

1. There is a maximum increase of 0.7 dBA in L_{eq} between the existing and design year conditions at two sites. The average increase is 0.4 dBA at a distance of 300 ft (91 m) from the near lane of the turnpike.
2. For 16 sites the noise level during the noisiest hour for the 2006 design year meets or exceeds the Pennsylvania Turnpike Commission Noise Abatement Criteria, which specify 65.5 dBA. The highest level is 71.4 dBA, an increase of 0.4 dBA from the existing 71.0-dBA noise level. This level is attributable mainly to the elevated position of this receptor above the turnpike and the lack of natural sound protection from the turnpike noise.

Mitigation Measures

Because of the limited right of way along the Pennsylvania Turnpike, one mitigation measure, noise barrier walls, is most effective for this project. Through consideration of the views expressed by the community, the needs of the turnpike maintenance policy and aesthetics, a system of precast concrete planks with exposed aggregate surfaces set between posts was selected. The planks were approximately 12 ft 3 in. by 4 ft by 6 in. (3.7 m by 1.2 m by 0.15 m) with a density of 150 lbs/ft^3 (2400 kg/m^3).

The total predicted 2006 design year noise levels at 16 receptor sites indicate the need for mitigation measures. Noise at 15 of the sites can be effectively mitigated through the use of noise barrier walls. The noise at one site can be mitigated through a combination earth berm/noise wall design.

A description of the noise barrier locations and noise mitigation effectiveness follows. Determination of actual costs was not possible because of the contractor's bid price; however, the estimate was approximately \$25/ft^2 (\$269/m^2).

Location A

This barrier will provide noise protection for receptor sites located on the south side of the turnpike. The proposed wall will be 14 ft (4.27 m) high and will provide at least a 3.5-dBA reduction to the affected receptors.

Location B

This 14-ft (4.27-m) noise wall, located along the north side of the turnpike and spanning a turnpike bridge structure, will provide noise shielding on the north side of the turnpike. The 6.4-dBA reduction will bring the projected noise level under the Pennsylvania Turnpike Commission's 65.5-dBA noise level criterion.

Location C

This noise wall will be 1,000 ft (305 m) long and will consist of a noise wall on earth berm design with a total height of 18 ft (5.49 m). The noise barrier will be situated on the south side of the turnpike. Noise mitigation will be 6.8 dBA, thus bringing the receptors under the 65.5-dBA noise level criterion.

Location D

This noise mitigation wall, 750 ft (229 m) long and 16 to 18 ft (4.88 to 5.49 m) high, will be situated along the north side of the turnpike. The noise reduction will be 4.9 dBA.

Location E

The proposed noise wall at this location, 3,600 ft (1099 m) long and 8 to 18 ft (2.44 to 5.49 m) high, will provide mitigation to the community south of the turnpike. For all receptors affected, the predicted noise will be reduced to a level below the 65.5 dBA criterion.

Location F

This noise abatement structure, 1,760 ft (536 m) long and 14 to 16 ft (4.27 to 4.88 m) high, is located along the north side of the turnpike. All projected noise levels at the affected communities will be reduced to a level below the 65.5 criterion.

Location G

The proposed noise mitigation wall at this location will shield receptor sites and the community located north of the turnpike. This 830-ft- (253-m) long and 10-ft- (3.05-m) high barrier wall will reduce the noise in this community to a level below the 65.5 dBA criterion.

NOISE STUDY—AFTER

Purpose

A noise study was undertaken after the turnpike widening project, including the described noise walls, to verify the noise levels predicted before construction. This task was prompted by requests of those property owners who were not affected by the mitigation measures and desired an extension of the newly constructed noise barriers.

Methodology

Noise monitoring was conducted at 20 noise sites in the same vicinity of the Pennsylvania Turnpike previously described. These noise sites included 8 primary sites and 12 secondary sites. The primary sites are residences of those who have filed complaints and the 12 secondary sites were chosen so that the 65.5-dBA (L_{eq}) noise contour could be established on both sides of the study section as a result of the field monitoring.

The noise monitoring procedures and techniques conform to the guidelines detailed in the FHWA Report, *Sound Procedures for Measuring Highway Noise: Final Report* (FHWA-DP-45-1R), and were conducted again during the noisiest time period between 3:00 p.m. and 5:00 p.m. (*8*). A type 1 Bruel and Kjaer Integrating Noise Meter (Model 2230) and Calibrator (Model 4230) were used. Both the noise meter and calibrator were factory calibrated before the field monitoring.

Results

The noise monitoring results reveal a decrease in noise level after the installation of noise walls. The decrease ranges from 2.9 dBA to 13.0 dBA and closely matches the predicted levels, adjusted for current traffic, before the installation of the barriers.

None of the noise levels at the eight primary sites exceed the Pennsylvania Turnpike Commission's noise abatement criterion of 65.5 dBA. Only one secondary site indicates a noisiest hour noise exposure of 66.2 dBA. This is attributable to the site's close proximity to a local road.

CONCLUSIONS

The methods employed in ambient noise monitoring, prediction, and mitigation design in the form of noise walls appear to be reasonably accurate, as demonstrated by a subsequent noise verification study following construction. This project involved noise impacts created by a high-speed, high-volume roadway.

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Airport Air Pollutant Inventories: Pitfalls and Tools

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This paper presents a description of common problems (pitfalls) and their solutions that occur during assessment of total air pollutant load from airport operations. Available computer tools are briefly discussed. Discussed in detail is the use and development of a microcomputer spreadsheet for conducting efficient emission inventories and the use of this spreadsheet as an effective planning tool.

Airports can be a significant local air pollution source and should be included in any local emission inventory. The requirements brought about by State Implementation Plans (SIPs) and federal environmental assessments (*1*) also make emission reporting a necessity. To prepare an emission inventory the air quality analyst must have adequate tools and methods to accomplish an accurate, comprehensive study.

Until recently, these tools and methodologies were confined to AP-42 (*2*) and a series of individual reports (*3,4,5,6*). Mobile sources accessing the airport required further references. The six major source types at airports (aircraft, support vehicles, stationary sources, fueling operations, fuel storage, and motor vehicles) had no overall documentation or methodology. This has led to certain problem areas. Accordingly, the authors' experiences showed that evaluation from airport to airport varied greatly in method and accuracy. In addition, outdated emission factors and incorrectly estimated times-in-mode led to inaccurate analysis.

This paper will report on the use of a microcomputer spreadsheet as an effective tool and provide methodologies to help the airport and air-quality analysts to avoid "falling into the common pitfalls" associated with airport air pollutant emission inventories.

THE EMISSION INVENTORY CONCEPT

The inventory of emissions permits a review of the total amount of pollutants emitted from a facility for a particular unit of time. To be consistent with local methodologies, usually the number of tons per year for most of the "criteria" pollutants listed in the National Ambient Air Quality Standards (NAAQS) are reported. These criteria pollutants include carbon monoxide, nitrogen oxides, sulfur oxides, hydrocarbons, and particulate matter. Notably, this list excludes lead (emitted in such small quantities from airport sources because of the use of low-lead or lead-free fuel that the results may be considered insignificant) and ozone (a secondary pollutant).

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The emission inventory may be sufficient to substantiate that there will be no significant impact. Accordingly, many airport air quality environmental assessments may not require an impact analysis, the next step beyond the emission inventory. Although an emission inventory cannot be used to directly demonstrate compliance with the NAAQS, the Federal Aviation Administration (FAA) requires the inventory as a first step to determine whether dispersion modeling is needed (*1*). Also, emission inventories are used to demonstrate consistency with the SIP by showing that the total pollutant load for an airport will not exceed the amounts planned for in the SIP. A direct comparison of emission inventories, present to future, is also usually adequate to evaluate the future scenarios for compliance with the SIP and the impact on the SIP of future scenarios, assuming that the SIP does not change.

The inventory permits trend assessment of any proposed project in three distinct ways. First, the inventory can be used to compare future project alternatives. The relative merits of each scenario, including the existing case and the do-nothing alternative, can be assessed. Second, the inventory can be used to compare future emissions to existing totals, to help analyze the effects of planned changes. Third, a comparison of project emissions to the total county inventory can be made. This permits an assessment of the relation between the proposed project and other major sources in the area, a very useful planning tool.

Airport sources may be separated into six distinct groups: (a) aircraft; (b) ground support equipment; (c) stationary sources (i.e., boilers, heating plants, etc.); (d) motor vehicles; (e) fuel storage; and, (f) fueling operations. Most large airports will have all of the six groups listed above. Stationary sources do not exist at all airports, however, and some airports may have other types of sources. Therefore, care should be taken to identify all sources at the start of the evaluation.

COMMON PITFALLS

Associated with each of the six source areas are problems or "pitfalls" that the air quality analyst must overcome. The following discussions, for each source, are methodologies that may be used to overcome the common pitfalls.

Aircraft

Large Commercial Aircraft

Data on the number of aircraft operations, aircraft type, and runway use must be accurately known. The collection of this data may involve consulting several sources. One complication that may be encountered is that each aircraft type may be equipped with several different engines, according to year of manufacture, retrofitting, and customer preference. It is not apparent which engine is in use, and most often a review of published sources and discussions with the aircraft manufacturers, airlines, airport, and the FAA are required to determine engine types for each aircraft model. (A starting point for engine type for each model of aircraft may be found in the periodical, *Aviation Week and Space Technology* (*7*). If several engines are used by airlines for a particular model of aircraft, efforts should be made to find percentages of each engine type. If this information cannot be quantified, the predominant type should be selected. When no one type dominates, the engine with the greatest amount of emissions should be assumed. In this way, the analysis is conservative and may overpredict, but not underpredict, emissions.

Selection of the wrong engine type can lead to large errors in the emission inventory. The common DC9 aircraft illustrates this point. Many engine types are possible for this aircraft (including the stretch design, DC9-80, commonly referred to as the MD80). Table 1 shows the emissions, by mode, for four common engine types used in the DC9 series. A review of this table shows the large differences that may occur in estimations from the various engine types. For example, for the crucial idle mode at airports, NO_x could be overestimated by a factor of 5.6 if the older JT8D-7 engine were assumed rather than the JT8D-9 or by 4.9 if selected over the JT8D-209. Figure 1 graphically shows the difference in carbon monoxide emissions for the four types of engines commonly used in DC9s. The new DC9-80 series shows marked improvement.

After the engine type for each aircraft is determined, emission rates for each are required. Emission rates for each engine type are a function of aircraft mode (idle, approach, climbout, and takeoff), time-in-mode, and fuel use. Each variable must be quantified. The EPA lists emission factors, per mode, for many types of aircraft in its publication AP-42 (*2*).

Unfortunately, AP-42 has not been updated for aircraft since February 1980. Since that time, manufacturers have made large strides in producing more efficient, cleaner engines. To overcome this difficulty, the FAA staff in Washington (Nicholas Krull, AEE-30) offers assistance by providing results from engine certification testing. The staff encourages the use of these factors where appropriate. FAA certification data, however, are only available for fuel use rates, hydrocarbons, carbon monoxide and nitrogen oxides, as well as a smoke number. Particulate and sulfur oxide data are not included.

Sulfur oxides may be estimated because sulfur oxides emissions from aircraft are a direct function of the sulfur content of the fuel. Jet fuel is highly refined and contains very small amounts of sulfur. The method used by the EPA in AP-42 is to multiply fuel usage rates by 0.001 (0.1 percent) to determine a conservative SO_x emission factor. This method may be used to supplement the certification data.

Particulate emission factors are not so easily predicted. Particulate emissions are not only a function of fuel type but also of engine efficiency, mode, and combustion chamber design. Particulate emissions are thus very difficult to quantify without extensive testing. As a first approximation, AP-42 values may be used for similar engine types with similar smoke numbers when only certification data are available.

Table 2 summarizes newer aircraft emission factors developed from FAA certification data for large commercial aircraft. This list may be used to supplement the values found in AP-42. It also should be noted that the certification data are in g/kg, but the AP-42 data are in lbs/hr or k/hr.

Time-in-mode data also need to be determined. Specifically, the landing/takeoff (LTO) cycle methodology within AP-42 may lead to large errors because of the differences that occur at individual airports. Indeed, the authors found a very significant overprediction of emissions during initial investigations of the Nashville and Los Angeles airports when LTO cycle data was used. For example, the LTO cycle given by AP-42 contains 26 min for taxi/idle (in and out) for commercial aircraft. Measurements made over many days at Nashville International Airport showed that the idle/taxi time was typically only 17 min. Accordingly, if the LTO cycle from AP-42 had been used at the Nashville airport, the idle/taxi time error could have resulted in an overprediction by a factor of greater than 1.5 while the aircraft was on the ground. It is important that the time-in-mode for idle/taxi be determined on a case-by-case basis for each airport, because these times change considerably from airport to airport. From a combination of the taxi and push-back times and the given runway use scheme, weighted average idle/taxi times can be derived for operations on each runway for individual airports. These times can then be combined on the basis of the annual percentage of use of each runway strategy. Care should be taken during peak periods to allow for additional time caused by queue lines. After all times-in-mode are determined, a new LTO cycle could be defined for each runway usage, or individual times-in-mode could be used and the results summed. For example, each aircraft type and different concourse use could have different times.

To determine times-in-mode when an aircraft is in the air, a 3,000-ft (912 m) inversion height and average mixing height above the ground is usually a good assumption (all emissions

TABLE 1 COMPARISON OF ENGINE TYPES: DC9 AIRCRAFT

MODE	DC9-50 JT8D-17	DC9-30 JT8D-9	DC9-10/20 JT8D-7	DC9-80 JT8D-209
IDLE				
FUEL USE	521.6	475.2	464.8	469.1
CO	17.7	16.4	16.5	6.6
NOX	1.8	1.4	7.9	1.6
HC	4.6	4.8	4.9	1.9
SOX	0.5	0.5	0.5	0.5
TAKEOFF				
FUEL USE	4527.0	3744.0	3528.7	4287.6
CO	3.2	4.6	5.3	4.4
NOX	91.9	67.1	9.5	97.8
HC	0.2	1.8	1.4	1.5
SOX	4.5	3.7	3.5	4.3
CLIMBOUT				
FUEL USE	3588.0	3056.4	2920.7	3538.1
CO	3.6	5.1	5.8	5.0
NOX	56.0	43.4	16.2	67.2
HC	0.2	1.4	1.5	1.8
SOX	3.6	3.1	2.9	3.5
APPROACH				
FUEL USE	1275.0	1072.8	1030.0	1293.1
CO	9.2	10.1	10.8	5.7
NOX	8.8	6.1	13.9	11.4
HC	0.6	1.9	1.6	2.2
SOX	1.3	1.1	1.0	1.3

SOURCE: JT8D-17 data from AP42; all others from FAA certification data.
NOTE: Values are shown in kg/hr.

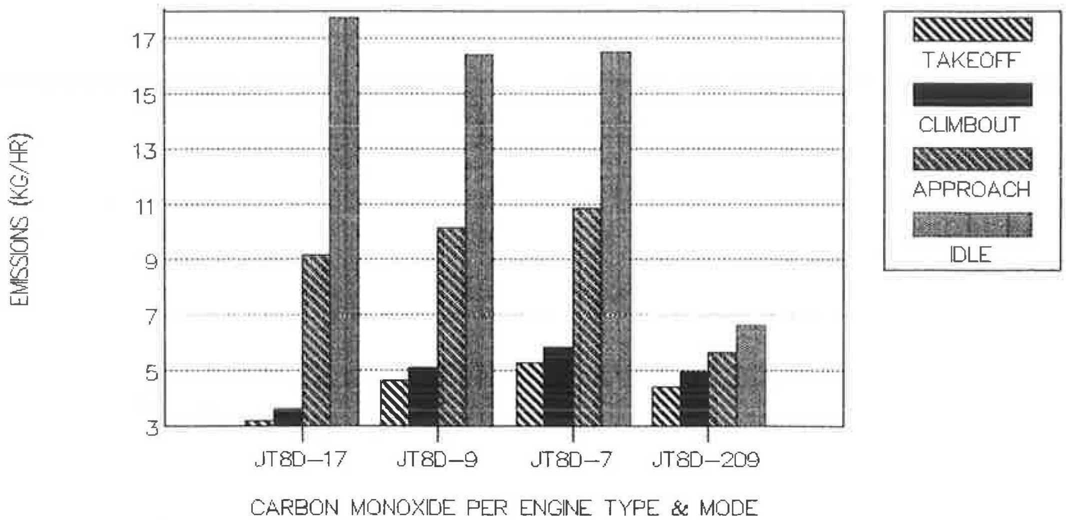

FIGURE 1 DC9-Type aircraft emissions compared—carbon monoxide only.

TABLE 2 FAA EMISSION INDEX[a]

Engine	Mode	Fuel Flow (kg/sec)	Emissions (g/kg) HC	CO	NO_x	Smoke No.[b]
PW 2037	Idle	0.1450	2.20	22.37	4.50	11.40
	Takeoff	1.5970	0.06	0.43	32.90	
	Climbout	1.3200	0.07	0.44	26.50	
	Approach	0.4080	0.20	2.23	10.60	
CF6-80A	Idle	0.1500	6.29	38.20	3.40	[c]
	Takeoff	2.1450	0.29	1.00	29.80	
	Climbout	1.7950	0.29	1.10	25.60	
	Approach	0.6150	0.47	3.10	10.30	
JT8D-209	Idle	0.1303	4.03	14.10	3.50	
	Takeoff	1.1910	0.35	1.03	22.80	11.10
	Climbout	0.9828	0.50	1.40	19.00	
	Approach	0.3592	1.69	4.37	8.80	
RB211-535C	Idle	0.2000	4.54	30.40	3.30	
	Takeoff	1.8040	0.27	1.37	31.79	
	Climbout	1.4740	0.23	1.00	26.59	14.87
	Approach	0.5440	0.15	2.26	9.85	
CFM56-3-B1	Idle	0.1210	1.83	31.00	3.90	
	Takeoff	1.0200	0.04	0.90	18.50	
	Climbout	0.8010	0.05	0.90	16.00	4.00
	Approach	0.3380	0.10	3.50	8.40	
JT8D-217R	Idle	0.1550	0.95	9.43	3.30	
	Takeoff	1.4170	0.21	0.95	25.30	
	Climbout	1.1030	0.27	1.03	17.60	19.60
	Approach	0.3755	0.53	2.54	8.40	
JT8D-7	Idle	0.1291	10.60	35.50	17.10	
	Takeoff	0.9802	0.40	1.50	2.70	
	Climbout	0.8113	0.50	2.00	5.55	22.20
	Approach	0.2861	1.60	10.50	13.50	
JT8D-9	Idle	0.1320	10.00	34.50	2.90	
	Takeoff	1.0400	0.47	1.24	17.92	
	Climbout	0.849	0.47	1.66	14.21	23.00
	Approach	0.2980	1.73	9.43	5.64	
ALF502R5	Idle	0.0408	5.39	40.93	3.78	
	Takeoff	0.3581	0.06	0.30	13.53	16.90
	Climbout	0.2955	0.05	0.25	10.56	
	Approach	0.1034	0.22	7.10	13.53	

[a]From FAA certification data.
[b]Maximum.
[c]Not given.

released within 3,000 ft (912 m) of ground level are considered). This assumption is consistent with AP-42, and airborne times shown by AP-42 may be used.

Smaller Aircraft and Military Operations

Emissions for general aviation aircraft, commuters, and military aircraft may be computed by assuming that the AP-42 landing/takeoff/cycles are applicable for generalized types. This approach is suggested because of the large differences in idle times that could occur because of irregular operations and the usually large number of different types of general aviation aircraft. This assumption may or may not be appropriate for all airports. The selection of these aircraft should follow the conservative procedure of selecting "dirty" engines when one type of aircraft does not dominate.

It should be noted that small aircraft emissions may be a significant contributor to the overall emissions depending on the airport operating characteristics. Accordingly, generalization of small aircraft could lead to errors in the predicted emissions. Each analyst should decide if a generalization of small aircraft is adequate or if a more detailed survey of small aircraft is required. Once again AP-42 emission factors will need to be supplemented with certification data because AP-42 lists only four general aviation piston aircraft types, four smaller turboprop types and five business jets.

Ground Support Equipment Emissions

If no detailed information on ground support equipment used at an airport is readily available, a methodology presented by FAA (*3*) may be used. The FAA report lists usage times for each service vehicle per aircraft type. Aircraft may need to be generalized into sizes to estimate support vehicle needs because no list of aircraft is available (*3*). The time per aircraft can be multiplied by the total number of operations during the time period under consideration, to estimate the total time for all operations. Next, the rate of fuel consumption may be used to determine total fuel use. From the total fuel use it is possible, using the given emission factors (*3*), to calculate the emissions for each ground service vehicle.

For this analysis, it is important to determine whether the service vehicles use gasoline or diesel fuel. Selection of the wrong fuel type can cause a significant error (pollutants other than the criteria pollutants may also be a concern here). For example, if gasoline vehicles are assumed, when in fact most are diesel, carbon monoxide will be overestimated by a factor of 6.7, hydrocarbons by a factor of 7.5, and nitrogen oxides, particulates, and sulfur oxides underestimated by factors of 2.7, 6.3, and 4.8 respectively.

Central Utility Plant (Boiler or Heat Generation Plant Emissions)

Stationary sources occur at many airports but are often overlooked in emission inventories. Care should be taken to assess the stationary sources that are present, their full use and any expected future changes.

AP-42 provides procedures for estimating stationary source emissions. The analyst, however, must determine future requirements and be careful when estimating future emissions to ensure: (a) that an unreal future demand is not put on existing facilities (if new facilities will be required these sources should be included); and, (b) that future fuel use and controls on emissions are considered.

Motor Vehicles

When predicting emissions from motor vehicles accessing an airport, two philosophies exist:

1. Emissions from motor vehicles should only be considered when the vehicles enter airport property and become part of the airport sources; or,
2. Emissions from motor vehicles should be considered when the vehicles start their journey to the airport because the entire trip is airport related.

For county inventories, coordination is needed to select a strategy to ensure that emissions are not counted twice.

If the entire vehicle trip to the airport is considered, two methodologies are available to the analyst. The first method is to conduct surveys of vehicles arriving at the airport to collect sufficient data so that total trip emissions can be determined. The other methodology would involve using one of several available trip generation models to determine zonal attractions for airport traffic, and from this calculate vehicle miles traveled and total emissions.

If only on-airport operations are considered, motor vehicle emissions will generally be smaller than aircraft emissions. This is an important consideration for the analyst during any planning process.

The data for on-airport vehicle operation are usually available for parking lots and loop road use from the local airport authority. Again, AP-42 values may be used or, if more accuracy is needed, available computer programs such as MOBILE-3 (*8*) should be used.

If specific statistical data of vehicle types using the airport are lacking, then national average emission factors should be used. According to an EPA document (*9*) for large urban areas, the national average specific percentages of vehicle types is 80.3 percent automobiles, 11.6 percent light trucks, 4.5 percent heavy gasoline trucks, 3.1 percent heavy diesel trucks, and 0.5 percent motorcycles. The national averages also assume 20.6 percent of the motor vehicles are operating in a cold condition and that 79.4 percent of the motor vehicles are operating in a stabilized condition with 27.3 percent having started hot.

These percentages may overpredict the amount of heavy trucks using the airport, which may cause a slight overprediction of emissions. Overprediction, however, is desirable for a first stage environmental assessment because if no problem exists when overestimations are used, then none would exist in a more precisely modeled situation. If problems do occur because of motor vehicle emissions, the analyst should strive to better define the motor vehicle traffic and mix.

Another pitfall that may occur at airports involves the method used to predict emissions from idling motor vehicles accessing the airport. This problem becomes more complex when predicting future emissions. The weighted average of vehicle types (i.e., taxi, limo, private auto) may be used to provide a representative idle time for passenger arrival and departure. This allows an efficient analysis because the weighted idle time may be multiplied by the number of vehicles for a total idle time at the terminal. This makes the effects of changes in passenger usage on total pollutant load easily quantifiable. The analyst should also be careful, however, to consider idle times in parking lots, at toll gates, etc. The equation used for weighted idle time would be:

$$t_{mv} = V_y[X_t(t_t) + X_a(t_a) + X_l(t_l) + \cdots X_n(t_n)] \quad (1)$$

where

t_{mv} = total idle time for motor vehicles in minutes
V_y = number of arriving vehicles/year,
X_t = proportion of taxis,
t_t = average taxi idle times in minutes,
X_a = proportion of private autos,
t_a = average private auto idle times in minutes,
X_l = proportion of limos,
T_l = average limo idle time in minutes,
X_n = proportion of nth vehicle type,
t_n = average idle time of nth vehicle type, and

$$X + X_a + X_l + \cdots + X_n = 1.0.$$

This produces total idle times for the analyzed situation in min/year. Of course to use this method, composite emission factors must also be determined in the same way mathematically:

$$EF_{mv} = X_t(EF_t) + X_a(EF_a) + X_l(EF_l) + \cdots X_n(EF_n) \quad (2)$$

where

EF_{mv} = composite emission factor, all vehicle types,
EF_t = average emission factor for idling taxis,
EF_a = average emission factor for idling autos,
EF_l = average emission factor for idling limos, and
EF_n = average emission factor for 11th vehicle type.

Then the product of t_{mv} will yield the total yearly pollutant load. In this form, planning and estimating future emissions becomes a simple task.

Fuel Storage

When liquid fuel is stored, releases of hydrocarbons to the atmosphere are inevitable. At any airport, the fuel storage methods must be determined.

The EPA has developed complex equations to estimate the hydrocarbon releases associated with breathing losses (L_B) and working losses (L_W) for several tank types and includes them in AP-42. Each variable in these equations must be determined on the basis of data provided by the airport or estimated from existing information.

Breathing loss emissions are caused by vapor expansion and contraction from changes in temperature and barometric pressure. The AP-42 report does not provide a clear methodology to be used at airports when the tanks are underground.

The average ambient diurnal temperature change (ΔT) for underground tanks is a direct function of the change in soil temperature. It can be assumed that the fuel temperature is approximately at ground temperature (except when fuel is first added to the tank). Temperature information may be found in the U.S. Department of Agriculture (USDA) Soil Conservation Service soil survey reports. The mean annual soil temperature for much of the United States may be estimated by adding 1.8°F (1°C) to the mean annual air temperature. Also, for soil depths greater than 39.4 in. (100 cm), diurnal changes are very small. Therefore, it can be assumed that the fuel temperature in underground tanks is equal to the average ground temperature, and remains relatively stable throughout the day (assumed 0.01°F change). This technique may be used at most sites.

Working losses are caused by filling and emptying the tanks. Vapors are expelled when the liquid level is increased; emissions also occur when the liquid level is drawn down, because air is drawn into the tank and gaseous expansion occurs.

The average space height must be estimated to predict working losses. If accurate data are not available, this can be done by the simplifying assumption that tanks are nearly drained before the delivery of new fuel. This conservative assumption could then be extended to the corollary that on the average, the tanks are one-half full and the average vapor space height is one-half the tank depth.

The paint factor allows for additional heating of darker tanks. For underground tanks this factor is inappropriate and should be set to 1.0.

The turnover factor can be estimated by assuming all tanks receive equal use. Then the turnovers per year could be estimated by:

Turnovers per year

$$= (\text{annual throughput})/(\text{tank capacity}) \quad (3)$$

The total annual throughput for each fuel type is usually accurately known.

For future scenarios, fuel use must be estimated. A conservative estimation can be determined by multiplying the ratio of the number of fuel-specific operations in the future compared to the existing case. For example, if aircraft operations are estimated to double by some future date, then it can be assumed that fuel use will also double. A better estimation can be made if the future fleet mix is known with some degree of certainty, and if the number of operations are known. Projected fuel loadings could then be multiplied by the number of expected future operations to determine total airport fueling operations. Each of these methods allows the turnovers per year to be estimated for the future case. From the estimated turnovers for each study year, a table provided in AP-42 is used to determine the turnover factor.

Once all the variables are quantified, the equations could be simplified for general use. Only selected variables need be changed (i.e., tank quantity or diameter) to determine the effects on emissions. This permits a very quick reestimation to examine various scenarios. The analyst should also be aware of tank age and the method of fuel transfer. Tank age would be important if leaks occurred at the seals. The method of transfer could result in fugitive hydrocarbon releases and is discussed in the next section.

Vapor recovery systems are being used much more frequently than in the past, sometimes as a requirement. If used, the recovery efficiency should be determined and the final results corrected.

FUELING OPERATIONS

Fugitive hydrocarbons are also released during the transfer of fuel. The EPA has developed emission factors based on the total amount of fuel transferred and has published these factors in AP-42.

The number of transfers must be determined to estimate the emissions. The analyst should determine how fueling operations are done at the airport under study (i.e., by trucks, pit hydrants, or other methods) because this will affect the number of fuel transfers. For example, if truck fueling is used, fuel is transferred from tanks to the truck and then to the aircraft (three transfers); however, if pit hydrants are used, fuel is only transferred to the aircraft from a pipeline (one transfer). From the number of fuel transfers, total hydrocarbon releases from fueling operations may be estimated. Care should also be taken to determine how the tanks are filled.

To estimate the hydrocarbon emissions from fueling operations, the number of gallons transferred per year are multiplied by the AP-42 emission factor. Emission factors are available for JP-4, diesel fuel, gasoline, and 100 L.L. (low lead) aviation fuel. Hydrocarbon releases caused by automobile fueling are generally smaller in comparison to the other fueling operation releases for any large airport because of the smaller volume actually pumped. Accordingly, these are sometimes eliminated from the analysis. Care should be taken to ensure that this is a valid simplification by reviewing total service vehicle and automobile fueling amounts.

EMISSION INVENTORY TOOLS

Procedures and tools have existed for some time for the conduct of airport air quality studies. These procedures (*2,3,4,5,6*) are informative and very useful. Unfortunately, no overall, comprehensive guide has been published describing the entire emission inventory process at airports. Accordingly, all of the steps needed to carry a comprehensive emissions study through to completion are not exactly clear.

FAA MODELS

Adding to the confusion was a general lack of comprehensive computer tools specifically designed for emission inventories. The lack of computer tools forced manual calculations, adding further chance for errors. The Airport Vicinity Air Pollution Model (AVAP) (*10*) has been available since 1975 and did combine all the sources in a single model. However, AVAP was designed for dispersion modeling and so requires extensive data input in a tedious fixed-field format (main-frame based). An emission inventory could be prepared using the output file, but only after extensive manual computations, which leads to the manual method problems noted above. Additionally, AVAP does not have updated emission factors for newer aircraft. Hence, although AVAP is a useful dispersion modeling tool, it is not a useful emission inventory tool.

FAA released a model called the Emission and Dispersion Modeling System (EDMS) (*11*) in December 1985. This model is microcomputer based and has all components of airport emissions in a single model. FAA's close dealings with airports led to this responsive model, which eliminated most of the problems of AVAP and allowed access to most airport operators because of the microcomputer base. Further releases in 1988 provided refinements and a more extensive data base. The primary output of this model is an emission inventory in a directly usable form. Although the title implies that dispersion modeling is accomplished, at this time the model-output is a completed emission inventory and an input file for dispersion modeling.

Because EDMS is ultimately meant to be a dispersion model, however, it also requires extensive inputting of data (for example, the sample problem requires 125 steps). Fortunately, this data is requested in a user-friendly, screen-prompted format. Much of the input is required for the creation of the dispersion modeling input file. This input file is directly compatible with the dispersion models contained in the Users' Network for Applied Modeling of Air Pollution (UNAMAP) system: (Point-Area-Line) (PAL) (*12*); HIWAY-2 (*13*); and, CRSTER (*14*). Quick analyses, as for planning, are not easily accomplished with EDMS. As the manual suggests, "An experienced user should be able to process the example problem in less than 3 hr." The authors required a quick, efficient way to compare multiple strategies and operations at the airports. Ultimately, a methodology and series of microcomputer spreadsheets were developed to permit quick calculations of emissions and easy revision of emission input data (*15*). The ability to quickly revise and recalculate was especially useful for studying the various project alternatives under consideration.

DEVELOPMENT OF THE SPREADSHEET

To permit the calculation of emissions easily and quickly, LOTUS 1-2-3 spreadsheets were developed. Originally, separate spreadsheet files were created for each source. Each spreadsheet contained a series of templates that allowed easy, user-friendly screen input, easily changed calculation sheets, and a summary table as the last template. Manual calculations were performed to validate each spreadsheet.

The concept behind these templates was simple and efficient (detailed programming of the spreadsheet is not described and the reader is referred to the LOTUS user manual (*16*). An auto-execute macro command places the user at the input screen at the beginning of the program. The initial use of the spreadsheet begins with all data ranges zero or blank and are shown as unprotected fields. User-friendly prompts such as "enter title" would be shown, but protected. In this way, only data entry fields may be changed and they are highlighted by being shown in a different color (for PCs so equipped). If more than one page of data entry is required, the user is advised to use the "page down" key to advance to the next data input screen. When all required data is input, the program prompts the user to review the data by scrolling, to change the data as needed, or to calculate the answer. Calculation is controlled by invoking a hidden macro command that calculates, first by setting variables as needed (for example, the fact that the year of analysis causes a significant change in motor vehicle emission factors is accounted for by macro manipulation of the data in the spreadsheet). Next, calculations are performed based on appropriate equations. Figure 2 shows an example of an aircraft calculation template. The screen is then placed at the cells containing a summary sheet. Of course, if the user wishes, changes may be made to data manually and manual updates used to calculate. Screen location may also be accomplished manually. This procedure, however, would eliminate a key element of the spreadsheet process, manipulation of the data to insure proper calculations.

Once a complete series of initial spreadsheet files (for each source) was created, the entire series was combined and integrated into a single spreadsheet. Data input was prompted by three input screens. Figure 3 shows a typical input screen. Calculations for all sources are based on these input screens and tabulated in an overall summary table. Variables (input data) are shared as needed for each source calculation. Input data are also stored for review and/or changes by simply scrolling to the correct input screen. Accordingly, only the affected spreadsheet cells would need to be changed to study each project alternative. For example, to study the effects of changes to the fleet mix, only the aircraft operations need to be changed. The variables for other sources may also be easily changed, however, by simply scrolling to the desired input sheet. After the new data for different alternatives are entered, a simple "recalculate" macro command is used to revise the calculations for all pollutants and all aircraft in a matter of seconds, and place the screen at the summary table. Figure 4 shows a typical summary table.

The completed, overall spreadsheet was designed as the individual sheets in three stages; input templates, calculation templates and summary template. Figure 5 shows graphically the concept behind the programming of individual templates for each source. In the overall spreadsheet, subtotal summary templates were also included to allow the user to look at the changes in total emission load for planning of a single source. Also, macro commands were used for overall control as well as for data manipulations. For example, key stroke sequences were coded into a macro command that enabled the movement of data blocks in the motor vehicle section, which allowed correct emission factors to be used for year of analysis.

This technique used a vehicle age and mileage weighting distribution, based on the national averages. According to the selected year, vehicle usage factors could "slide" to the appropriate cells to allow calculation of an overall composite emission factor for each vehicle tape. This follows the methodology of AP-42 (*2*). This calculation technique was the same as shown in Equations 1 and 2.

Subsequent uses of the spreadsheet are very fast, because the user may store the results of previous calculation sections under different file names. Then, as changes occur, the user

AIRCRAFT: 727-200 ENGINE TYPE: JT8D-17 3 ENGINES A-11

YEAR: 1986

MODE	FUEL USE (LB/HR)	TIME/OPER. (MIN)	LTO PER YR.	TOT. TIME (HRS)	TOTAL FUEL USED (LB)
IDLE	1150	12.61	44421	9336	10736064.
TAKEOFF	9980	0.53	44421	392	3915963.2
CLIMBOUT	7910	2.20	44421	1629	12883425.
APPROACH	2810	4.00	44421	2961	8321440.3

POLLUTANT	MODE	EMISSION RATE (EPA)	EMISSIONS PER MODE	TOTAL EMISS.
CO	(IDLE)	39.10	1095079	1321682
	(TAKEOFF)	6.99	8228	
	(CLIMBOUT)	7.91	38650	
	(APPROACH)	20.23	179725	
NOX	(IDLE)	3.91	109508	1123224
	(TAKEOFF)	202.60	238489	
	(CLIMBOUT)	123.40	602964	
	(APPROACH)	19.39	172263	
HC (-CH4)	(IDLE)	10.10	282872	297942
	(TAKEOFF)	0.50	589	
	(CLIMBOUT)	0.40	1955	
	(APPROACH)	1.41	12527	
SOX	(IDLE)	1.15	32208	107571
	(TAKEOFF)	9.98	11748	
	(CLIMBOUT)	7.91	38650	
	(APPROACH)	2.81	24964	
SPM	(IDLE)	0.36	10083	40468
	(TAKEOFF)	3.70	4355	
	(CLIMBOUT)	2.60	12704	
	(APPROACH)	1.50	13326	

FIGURE 2 Aircraft emissions calculation spreadsheet based on AP-42 emission factors.

PLEASE ENTER YEAR OF ANALYSIS: 1986 PAGE A-2

**********COMMERCIAL AIRCRAFT INPUT**********
PLEASE ENTER THE LTO CYCLES AND TIME IN MODE FOR EACH AIRCRAFT TYPE

AIRCRAFT TYPES	# LTO'S PER DAY	*TIME IN MODE (AVG. EVENT IN MIN.)* TAXI/IDLE	TAKEOFF	CLIMBOUT	APPROACH
A300	8.9	16.22	0.63	2.20	4.00
B707	0.4	15.46	0.53	2.20	4.00
B727	121.7	12.61	0.53	2.20	4.00
B737	114.7	12.61	0.53	2.20	4.00
B737-300	14.4	12.61	0.53	2.20	4.00
B747-100	11.8	16.22	0.63	2.20	4.00
B747-200	27.3	16.22	0.63	2.20	4.00
B747-SP	3.6	16.22	0.63	2.20	4.00
B757-200	9.7	15.46	0.53	2.20	4.00
B767-200	18.6	16.22	0.63	2.20	4.00
BAe146	35.8	12.61	0.53	2.20	4.00

**********FUELING, STATIONARY, AND MOTOR-VEHICLES INPUT******PAGE A-5

	ENTER
FUELING DATA	
ENTER NUMBER OF JP-4 FUEL TANKS ON AIRPORT:	23
ENTER AVG. DIAMETER OF ALL TANKS (FT):	20
ENTER THE EFFECTIVENESS OF VAPOR RECOVERY (%):	85
STATIONARY SOURCE DATA (TWIN TURBINES)	
ENTER FT3/100 OF NATURAL GAS USED PER YEAR:	5137385
ENTER GALLONS OF DISTILLATE FUEL USED:	274086
ENTER THE PER CENT (BY WEIGHT) OF SULPHUR IN FUEL:	0.045

MOTOR-VEHICLE DATA
ENTER AADT (VEH/DAY): EMPLOYEE: 45167 ALL OTHER: 63000
FOR "ALL OTHER": ENTER % BUS: 3.3 % TRUCK: 0
ENTER TRIP LENGTH (MI.): EMPLOYEE: 20 ALL OTHER: 46
ENTER DAILY AVG. PARKING LOT USAGE (VEH/DAY): 34673
ENTER AVG. IDLE TIME AT TERMINAL (MIN): 2

TO COMPUTE RESULTS, PRESS ALT-A, TYPE ANALYSIS YEAR AND HIT ENTER.

FIGURE 3 Typical spreadsheet input screens.

*****SUMMARY OF RESULTS*****

SOURCE	POLLUTANTS (TONS/YR) CO	NOX	HC	SOX	SPM
AIRCRAFT	4,331.6	3,546.4	1,629.4	690.4	107.2
GRD VEHICLES	1,171.9	66.9	261.9	0.9	2.1
FUELING EVAP.	---	---	263.4	---	---
STAT. SOURCES	5.8	28.4	1.4	1.0	1.6
MTR-VEHICLES	28,475.2	2,582.2	2,740.3	351.5	916.8
TOTALS	33,984.5	6,223.9	4,896.3	1,043.8	1,027.7

FIGURE 4 Summary page from spreadsheet.

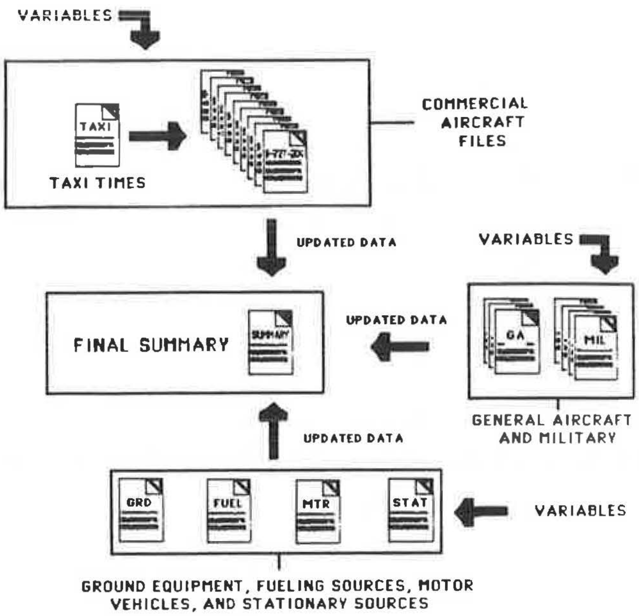

FIGURE 5 Conceptual design of airport emissions inventory spreadsheet methodology.

simply recalls the proper spreadsheet, makes the required changes, and recalculates. Many scenarios can thus be evaluated quickly.

SUMMARY

This paper presents suggestions to overcome common problems (pitfalls) and a computer methodology to estimate air pollution emissions from airports. The computer methodology presented may be used at any airport. Table 2 presents emission factors from FAA certification data that should save a great deal of time and increase accuracy in future studies. Methodologies for determining aircraft taxi time and automobile idle time have also been presented. This work should help other analysts by saving considerable time and effort in conducting similar analyses to allow quick efficient planning methods and emission inventories.

A conservative approach is suggested to ensure that any problem areas would be identified. For example, if the project alternatives had shown great differences or if noncompliance with the SIP had occurred, then a more detailed examination, and perhaps dispersion modeling, would be necessary.

A key factor in estimating emissions is the amount of taxi/idle time required for the aircraft. Accordingly, great effort should be made to quantify this factor. If the suggested AP-42 techniques are used alone, errors may occur because of (a) outdated emissions factors; and (b) excessive idle times based on a very large, congested airport. Accordingly, the methodology and emission factors of this paper are thought to give much more reasonable results.

FAA computer tools available to the analyst are not meant primarily for emission inventories and require extensive data input. The authors have found that the use of LOTUS 1-2-3 spreadsheet templates allows quick and efficient estimates of changing criteria through data storage in input templates.

Emission inventories may be completed quickly and efficiently. Emission inventories can be valuable planning tools. The computer methodology presented here for conducting an emission inventory allowed the future cases to be adequately analyzed and also allowed the inventories to be input for project decision making. Although the results should not be used to predict impacts (dispersion modeling is required for that), comparisons between project alternatives, changes from existing emissions, and changes in countywide emissions may all be studied. The time required for such an analysis in the future should be reduced by using the information collected by the authors and the microcomputer methodologies presented herein.

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Environmental Impact Analysis of Transportation in a Rapidly Developing Urban Area

P. A. Koushki

The environmental impact of transportation systems on air quality and noise levels is analyzed for the rapidly developing capital city of Riyadh, Saudi Arabia. In addition to monitoring noise and carbon monoxide during peak- and off-peak hours at heavily traveled urban arterials, physical, land use, traffic volume, and travel speed data were also collected at study locations. Findings indicated that traffic-generated noise and carbon monoxide air pollution were in excess of permissible standards by a considerable margin. Both traffic volume and travel speed demonstrated significant and positive correlations with the various statistical measures of traffic noise. Traffic volume, wind velocity and traffic speed were also significantly correlated with carbon monoxide concentrations. It appears that rapid urbanization, increased mobility and the favoring of private transportation modes by responsible authorities have combined to create a significant negative impact on the urban environment. Finally, the policies for mitigating the adverse effects of traffic noise and air pollution in developed nations are reviewed, and their applicability to the case of Saudi Arabia is discussed.

This paper reports on the findings of two research projects aimed at analyzing the environmental impacts of transportation in Riyadh, the rapidly developing capital of the Kingdom of Saudi Arabia.

Over the last two decades, the environmental impact of transportation in urban areas has become a major public concern in western industrialized nations and, as such, has received increased attention from federal, state and local governments, the private sector and the public. In response to this growing concern, governments and authorities have committed considerable resources to control these negative side-effects of transportation, and the end result has been successful to a remarkable degree (*1*).

Air and noise pollution constitute two of the most critical areas of the environmental impact of transportation. Through multidimensional and concerted efforts to improve environmental quality, the governments of Western nations have established laws and regulations (*2,3*). Researchers have identified sources of these pollutants and have developed measurement methodologies (*4,5,6*) and predictive models to determine the future impacts of these substances (*7,8,9*). Furthermore, they have examined the assumptions (*10*) and reliabilities of these models (*11*), and established design methods and expert systems for the mitigation of these substances (*12,13*) and for policy analysis (*14*). Finally, they have addressed the public's attitudes toward (*15,16*) and responses to these environmental impacts of transport systems (*17,18,19*).

In the Kingdom of Saudi Arabia and other nations of the Persian Gulf, the rate of socio-economic and infrastructural development over the last decade and a half has been unparalleled in the history of the modern world (*20*). From 1971 to 1987, this development has directly affected urbanization and mobility trends in these nations. The population of Riyadh grew from 350,000 to 1.3 million (*21*). The number of registered vehicles in the kingdom also increased more than 30 times during the same period (*22*). An average Saudi household in Riyadh owns nearly two autos and makes more than eight vehicle trips per day for a total of nearly 90 km of travel (*23*). A major arterial street in the city center may carry an average daily traffic volume of well in excess of 150,000 vehicles per day (vpd) (*24*). A large percentage of these daily traffic volumes consists of station wagons, minibuses, buses and heavy commercial vehicles (*25*). Despite these tremendous increases in the size of the urban population, the vehicle fleet and daily travel, recent research concerning the environmental impact of transportation in the kingdom is extremely limited.

This paper presents the findings of two funded research projects designed to monitor and analyze traffic carbon monoxide (CO) and noise pollution in Riyadh and to recommend policies for mitigating the adverse effects of these pollutants.

The objectives of these studies were to: (a) monitor CO and noise pollution levels in heavily-traveled arterial roadways in Riyadh; (b) examine the contributing power of the causal factors of traffic volume, speed and mix, roadway geometrics and meteorological characteristics on these pollutant levels; and (c) review and recommend mitigation policies applicable to urban areas of the kingdom.

EXPERIMENTAL DESIGN

Eight locations were selected for CO and noise monitoring. These roadway sites were chosen on the basis of frequent site visits and discussions with traffic officials. Location, land-use, and physical data were collected, and traffic volume was measured continuously for a period of 2 weeks at each location. Traffic speed was also measured during 6 peak hours spread over the study period (1985–1986). Table 1 presents a summary of the land use, physical, and traffic characteristics for the study arterials.

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TABLE 1 LAND USE, PHYSICAL, AND TRAFFIC CHARACTERISTICS OF THE STUDY ARTERIALS

Arterial Roadway	Major Land Use Type	Approach Width (m)	Sidewalk Width (m)	Street Aspect Ratio	Peak-Hour Volume (vph)	Peak-Hour Speed (kph)	Monitoring CO	Monitoring Noise
Al-Batha	Commercial/ Residential	12.0	4.8	0.5	3630	22.0	•	•
Al-Jameah	Gov't/ Residential	12.0	4.5	0.1	7124	21.5	•	
Al-Washem	Commercial/ Residential	12.0	5.0	0.5	6750	17.0	•	•
Al-Matar	Gov't/ Commercial	11.5	4.9	0.1	2685	21.0	•	
Al-Khleeg	Gov't/ Commercial	7.0	1.5	0.1	4388	26.0		•
Al-Aseer	Residential/ Commercial	7.5	4.5	0.8	4036	19.0	•	
Al-Madinah	Commercial/ Residential	12.0	2.7	0.4	2040	23.0	•	
Al-Senaeiah	Industrial/ Commercial	13.0	2.0	0.1	4307	27.0		•

Traffic noise was measured during 6 hr covering the morning and the evening peak periods and the off-peak hours at each location. Noise levels were recorded at 1-min intervals using the Bruel and Kjaer Sound Level Meter Type 2209 and the Sound Frequency Filter Type 1616. These instruments were calibrated before each monitoring period.

Carbon monoxide was measured at each location during 6 peak hours spread over a 3-month period (October–December) in each year. Concentration levels were recorded three times at 5-min intervals during peak hours. Concentrations of CO were also monitored continuously for a period of 10–15 days at each arterial. Ecolyzer Series 2000, together with Rustrak Recorders Model 288, were used to monitor for CO. These instruments were also calibrated before each measurement period.

TRAFFIC NOISE

Analysis of noise level measurements indicated that traffic noise was quite high at all locations and during peak and off-peak periods. Noise levels ranged mainly from the high 70s to the low 90s, and their intensities differed from location to location.

A sample of the cumulative frequency distribution of noise levels for the Al-Batha and the Al-Washem arterials is shown in Figure 1. Noise levels in the Al-Batha site fluctuated from a low of 81 dBA to a high of 96 dBA during peak and off-peak periods. The values of L_{10}, L_{50}, and L_{90} (the sound pressure levels exceeded 10, 50, and 90 percent of the time, respectively) were 91.9, 86.8 and 83.1 dBA, respectively.

At the Al-Washem site, noise levels ranged from a low of 66 dBA to a high of 95 dBA. As shown in Figure 1, this site was considerably less noisy, in general, than the Al-Batha roadway. The main reason for the higher noise levels in Al-Batha was the location of a steel flyover constructed to permit through traffic to bypass the signalized intersection with Al-Khazzan Street. In addition to the reflective noise, the through traffic over the flyover travels at a high speed, even during daily rush hours.

A summary of the L_{10}, L_{50}, L_{90}, L_{eq} (the equivalent sound level, or the sound pressure level of a constant noise that produces the same amount of acoustic energy over a given time period as the actual noise varying over time), L_{NP} (the noise pollution level) and *TNI* (the traffic noise index) for three monitoring periods and four study sites is presented in Table 2. It is important to note that traffic noise was generally

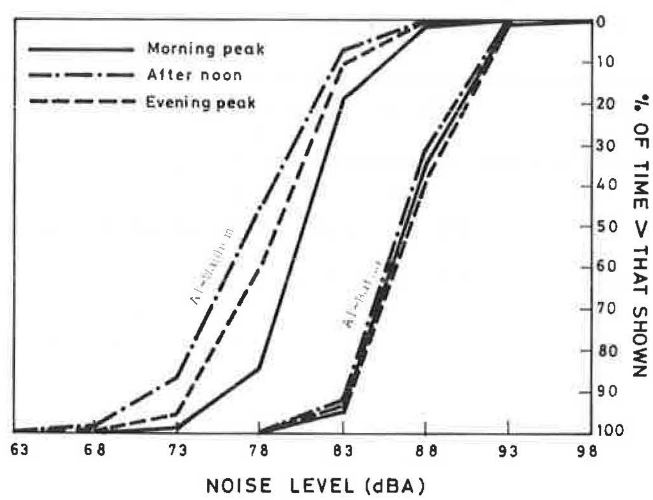

FIGURE 1 Cumulative distribution of noise levels at Al-Batha and Al-Washem.

TABLE 2 SAMPLE NOISE LEVEL MEASURES AT MAJOR ARTERIALS IN RIYADH

Study Site	Monitoring Time Period	Noise Level Measures (dBA)					
		L_{10}	L_{50}	L_{90}	L_{eq}	L_{NP}	TNI
	Morning Peak	92	87	84	91	97	86
Al-Batha	Off-Peak	91	86	83	90	96	86
	Evening Peak	92	87	83	91	97	87
	Morning Peak	86	81	76	84	92	84
Al-Washem	Off-Peak	83	78	72	82	91	81
	Evening Peak	83	79	74	83	91	85
	Morning Peak	87	82	78	85	93	83
Al-Senaeiah	Off-Peak	85	80	74	83	91	85
	Evening Peak	87	80	75	85	96	94
	Morning Peak	89	85	80	89	96	85
Al-Khaleej	Off-Peak	82	77	73	81	88	77
	Evening Peak	87	82	78	85	92	83

very high during working hours at all sites. This is clearly evident from the values of the L_{90}. The L_{90} ranged from a low of 72 dBA (off-peak period) at the Al-Washem site to a high of 84 dBA during morning peak hours at the Al-Batha location.

The L_{eq} was also calculated for each monitoring period. The resulting L_{eq} values ranged from a low of 81 dBA at the Al-Khaleej site to a high of 91 dBA at the Al-Batha location. The L_{eq} values remained nearly constant at all sites with the exception of the Al-Khaleej location, where fluctuations of traffic volumes between peak and off-peak hours were the most pronounced of all sites.

In terms of assessing the effects of noise on humans, L_{eq} is one of the most important measures of environmental noise, because experimental evidence suggests that it accurately describes the onset and progression of hearing loss. There is also considerable evidence that L_{eq} measures human annoyance attributable to noise.

Also presented in Table 2 is the calculated value of the L_{NP} for each monitoring period. The L_{NP} values were generally in the high 90s, indicating the "noisiness" of major arterial roadways in Riyadh. The L_{NP} was less than 90 dBA only during the off-peak hours at Al-Khaleej site.

The *TNI*, which records the frequencies of intruding single-event noises such as the sounds of sirens, horns and noises from heavy trucks, again indicated that although the noise levels during any period of study were generally uniform, the intruding single-event noises were sufficiently frequent to affect the values of the L_{10} (the highest-intensity noise levels). This was particularly true at the Al-Khaleej roadway, which is located next to the Military Hospital.

A comparative analysis of the *TNI* and the L_{eq} noise levels indicated that the *TNI* values are mostly larger than the L_{eq} levels. This reflects the fact that although the noise levels during any period of the day were generally constant, the intruding single-event noises were sufficiently frequent to affect the values of L_{10}, and consequently, the *TNI*.

It is of particular importance to note that in urban areas of the Middle East in general and the Kingdom of Saudi Arabia in particular, the lifestyle and the consequent variations in travel behavior assume a significantly different pattern than those of urban areas in industrialized nations. Instead of the two typical daily rush hours (start and end of daily working hours) experienced in urban areas of Western nations, traffic patterns on a given day follow four peak periods in the kingdom's cities. The usual morning peak is followed by an early afternoon (1:00 p.m.–3:00 p.m.) peak corresponding to the closing down of commercial activities and the end of the working day for government agencies and educational institutions. The third daily peak occurs at 4:00 p.m.–5:00 p.m., when commercial and private-sector institutions resume their second (evening) working period. The last, and usually the heaviest, daily traffic peak is around 8:30 p.m.–9:00 p.m., when the daily working hours end. Clearly, this pattern of daily travel significantly affects the impact of transportation on the urban environment.

Table 3 presents the results of the correlation analysis performed on traffic volumes, travel speeds and statistical measures of traffic noise. Both volume and speed of traffic demonstrated a relatively high positive correlation with the statistical measures of L_{10}, L_{50}, L_{90} and the L_{eq}. The coefficient of correlation between traffic volume and speed, however, had a negative sign, indicating a decrease in travel speed with an increase in traffic volume, as was expected.

TRAFFIC CARBON MONOXIDE

The peak hour distribution of carbon monoxide concentrations indicated that the levels of CO air pollution at all sites were generally above the standard limit. The Saudi Arabian Air Quality Standards (SAAQS) limit the concentrations of carbon monoxide to 35 ppm, for maximum 1-hour exposures and to 9 ppm for maximum 8-hour exposures (*26*).

A typical distribution of carbon monoxide concentrations during a peak hour for the two study periods is shown in Figures 2 and 3 for the Al-Batha and the Al-Jameah roadways, respectively. The CO levels represent the average levels of

TABLE 3 SIMPLE CORRELATION MATRIX

Variable	Variable L_{10}	L_{50}	L_{90}	L_{eq}	Avg. vol./hr	Avg. speed/hr
L_{10}	1.0000	.9647	.9951	.9701	.5893	.5219
L_{50}		1.0000	.9750	.9997	.4480	.4743
L_{90}			1.0000	.9800	.5065	.4175
L_{eq}				1.0000	.4534	.4331
Avg. vol./hr					1.0000	−.3107
Avg. speed/hr						1.0000

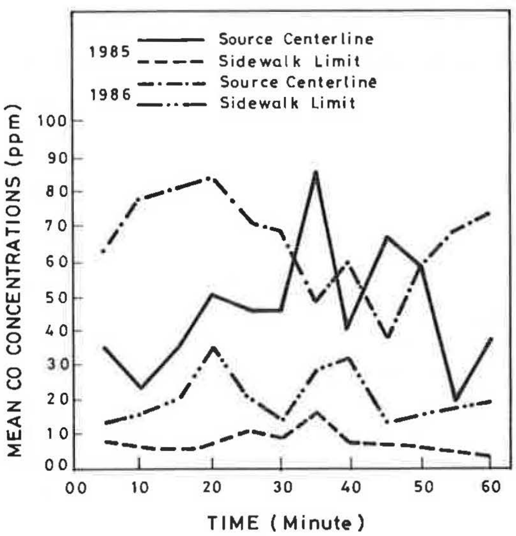

FIGURE 2 Peak hour distribution of carbon monoxide concentrations at Al-Batha.

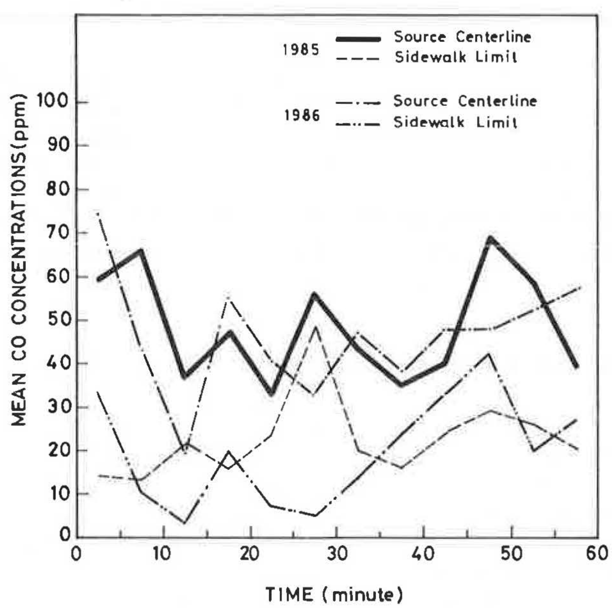

FIGURE 3 Peak hour distribution of carbon monoxide concentrations at Al-Jameah.

six peak hour periods monitored each year. The concentrations of CO increased slightly during the two study periods. This increase in CO levels was in line with the increase in the number of vehicles in Riyadh (*27*). The CO levels decreased significantly with increasing distance from the source.

The variations in the peak hour CO distributions are mainly attributable to fluctuations in traffic volume and timings of traffic signals at one end of the study sections. The construction of various urban roadways over the last decade in general, and that of the ongoing north-south cross-town expressway in particular, have resulted in numerous short- and long-term traffic detours, causing a shift in volume at or in the vicinity of the study locations. In addition, the timing of the isolated traffic signals throughout the city is frequently manually adjusted (by traffic officials) to accommodate variations in traffic volume attributable to detours or congestion during peak hours, or both. Both factors may affect CO concentrations significantly.

Factors of wind direction and velocity may also significantly contribute to these variations. Analysis of wind data for the two study periods, for example, indicated that although wind velocity varied between 5.6 and 18.5 km/hr at different monitoring days during the first study period, it changed from 1.9 to 9.3 km/hr in the second study period. The direction of wind was never the same for any corresponding monitoring day during the two study periods (*28,29*). Measurements of background CO levels at a farm 75 km from Riyadh indicated that the 1985 maximum 1-hr and 8-hr concentrations were 2.4 and 1.3 ppm, respectively.

The result of two weeks of continuous monitoring of CO taken at a height of 3 m (sidewalk limit) at each study section also indicated that the maximum 8-hr average concentration of CO exceeded the standard limit by a substantial margin at all locations. The 8-hr levels in Al-Jameah ranged from 15 to 31 ppm, for an average of 22 ppm. The CO mean 8-hr concentrations at Al-Batha and Al-Aseer were 21 and 14 ppm, respectively.

The cumulative frequency distribution curves of continuous CO measurements for the Al-Jameah and Al-Aseer sections are shown in Figure 4. These distributions indicate that the CO concentrations in Al-Jameah have, in general, a higher probability of exceeding a given level than those for the Al-Aseer roadway, especially at higher concentration levels. For example, although the concentrations of CO at Al-Jameah exceeded 22 ppm 50 percent of the time, those at the Al-Aseer roadway were less than 15 ppm. The difference in the daily CO concentration distributions between the Al-Jameah and Al-Aseer roadways is caused mainly by two factors: the average daily traffic volume and the street aspect ratio (the ratio of building height to street width). The Al-Jameah roadway is a major arterial serving a variety of commercial, educational, and residential land uses. In addition, it serves as a link connecting the newly developed districts in the northeast of the city to the CBD area. As such, this arterial roadway moves large volumes of traffic throughout the day. Al-Aseer Street, on the other hand, is a collector serving a mainly residential district with high volumes of traffic during the daily rush hours and low volumes of local traffic during off-peak hours. The street aspect ratio for Al-Aseer Street is also eight times higher than that of Al-Jameah Street (Table 1).

The mean CO concentrations measured during the 1985 and 1986 study periods were subjected to a significance test to determine whether the increases or decreases in their levels were statistically significant (*30*). As presented in Table 4, the increases in source-centerline concentrations at Al-Batha and Al-Jameah, and the decrease in CO levels at Al-Aseer over the 2-year period were not significant at the 95 percent significance level ($\alpha = 0.05$).

Analyses of correlations, performed to determine degrees of linear association between CO levels and causal factors, indicated that variables of traffic volume, wind speed and traffic speed demonstrated a significant correlation with the levels of CO concentrations. The coefficient of correlation between the peak hour traffic volume and mean 1-hour CO concentrations varied from a low of .39 at Al-Jameah, to .64 at Al-Batha, and .71 at the Al-Aseer arterial. Those for the mean wind velocity were −.28, −.46, and −.52 for the Al-Jameah, Al-Batha, and Al-Aseer roadways, respectively. The correlation coefficients between traffic speed and CO levels were −.21 for the Al-Jameah, −.36 for the Al-Batha, and −.33 for the Al-Aseer arterial. The negative signs associated with these coefficients conformed to expectations. Both traffic speed and wind velocity demonstrated a negative relationship with concentrations of CO, indicating a reduction in CO levels as the value of these variables increased (*31*).

The error associated with the sample mean of CO was calculated and a mean confidence interval was constructed using the CO sample size, the mean and the standard deviation for each sampling location. For example, the errors associated with the 1985 sample CO were ±1.7, ±1.4, and ±1.2 ppm at Al-Batha, Al-Jameah and Al-Aseer, respectively. The true mean CO concentrations at Al-Batha, for example, fell within a range of 59 to 62 ppm 95 percent of the time. Because

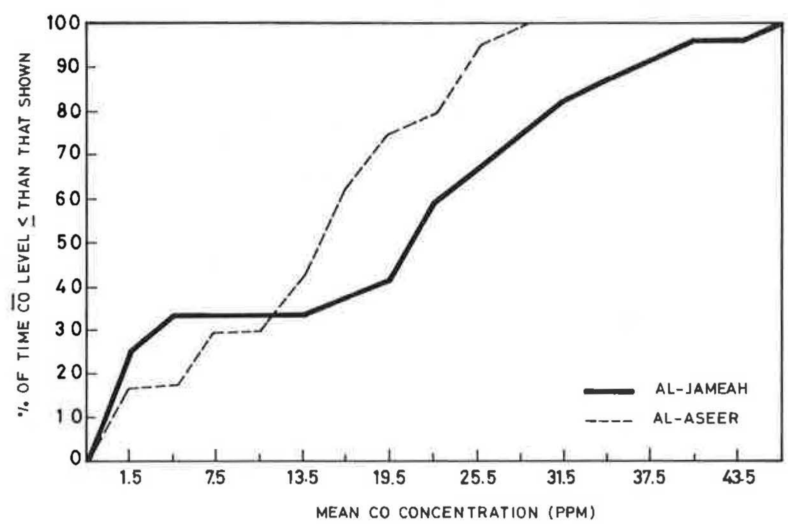

FIGURE 4 Cumulative distribution of carbon monoxide concentrations at Al-Jameah and Al-Aseer.

TABLE 4 TEST OF SIGNIFICANT DIFFERENCES IN MEAN CO CONCENTRATIONS (1985–1986) (*30*).

Arterial Roadway	1985 μ_1	σ_1	N_1	1986 μ_2	σ_2	N_2	Calculated Z Value	Hypo. Test $H_0 = \mu_1 = \mu_2$ $H_1 = \mu_1 = \mu_2$
Al-Batha	60.3	10.1	216	58.6	10.3	108	1.4	H = Rejected
Al-Jameah	48.4	8.4	216	54.6	8.1	108	.31	H = Rejected
Al-Aseer	50.8	9.6	216	57.5	11.7	108	-1.6	H = Rejected

NOTE: 95 percent significance level ($\alpha = .05$) used.

of the smaller sample size, the 1986 CO levels are characterized by slightly less accurate sample means than those of 1985 at all study arterials.

MITIGATION POLICIES

Western developed nations, through their pioneering in technological innovations and utilizations, have provided the developing nations with two valuable opportunities. The preventive opportunity is the opportunity to learn from mistakes and inappropriate policy decisions concerning the adverse effects of intensive use or misuse of technology. The option opportunity is the opportunity to choose (with a minimum of resource expenditures) from among a set of tested and evaluated mitigation policies, those that are best suited to a particular socioeconomic and political environment.

The widespread occurrences of similar adverse environmental impacts in many of the developing countries indicate that unfortunately, valuable advantages of the preventive opportunity have yet to be realized by these nations. In spite of several decades of advance warnings, similar mistakes are being repeated. The kingdom has assumed a pioneering role in the region by taking steps to control the adverse effects of transportation on the environment.

Mitigation and effective control of the adverse effects of traffic noise and air pollution require approaches that in many respects are complementary. A mitigation policy such as land use control, traffic management, or transit promotion that is directed toward one type of pollution often minimizes the negative impacts of the other.

Control approaches may be grouped into five categories:

1. Source emission control
2. Improved highway design noise barriers and vegetation
3. Land use control
4. Traffic management and transit promotion
5. Public education program

Source Emission Control

Source emission control requires the development of vehicles that are quieter and emit less CO air pollution. Significant progress has been made by vehicle manufacturers over the last decade to reduce both vehicle noise and CO emissions, and it continues to be made. The role of governments has been to establish and enforce noise and CO emission standards. The kingdom has adopted the CO emission standards of the United States and, through the establishment of the Vehicle Inspection Program (now 2 years into operation), enforces the 35 ppm, maximum 1-hr concentration levels. Similar efforts, however, are required to regulate levels of noise and reduce high noise pollution levels at certain locations.

Improved Highway Design and Noise Barriers

The Federal Highway Administration FHWA regulations for mitigating traffic noise in the planning and design of highways include adequate noise abatement measures to comply with the standards, and a greater attention to noise impacts in choosing the route and layout of new roadways (*32*). The regulations require that the following factors be considered during the planning and design phases of a roadway project: identification of traffic noise impacts; examination of potential mitigation measures; incorporation of reasonable and feasible noise mitigation measures into the highway project; and coordination with local officials to provide helpful information on compatible land use planning and control.

Because roadway networks of most major urban areas in the kingdom have been completed recently and very few new highways are being built within populated areas (with the exception of the north-south cross-town expressway in Riyadh), the choice of realigning or depressing the roadway is not available. The construction of noise barriers along the newly constructed urban expressways may, however, provide the most effective measure for reducing traffic noise along these corridors, where necessary.

Noise barriers may also be constructed along the existing steel flyovers and bridges within urban areas. These urban roadway sections currently experience noise levels much in excess of the permitted standards. Effective noise barriers can reduce noise levels by 10 to 15 dB, thereby cutting the loudness of roadway noise in half.

Land Use Control

Land use control is concerned primarily with establishing and enforcing regulations on land development so that noise-sensitive land uses are either prohibited next to a roadway, or so that developments are planned, designed, and constructed in a way that minimizes traffic noise impacts.

In developed nations, control of land use development is mainly the responsibility of local governments. In Saudi Arabia, however, the unified central government structure is best suited to the application of this mitigation measure because the bureaucracy and red tape involved in dealing with thousands of local governments is reduced.

Traffic Management and Transit Promotion

Options in this category include the rerouting of heavy vehicle traffic; the prohibition of trucks from certain streets and/or the assignment of a specific time period for their operation; the evaluation of traffic signal timings and their coordination to minimize frequent stops and starts; the reduction of speed limits, especially at locations with steel flyovers or bridges; the evaluation of one-way/two-way operation to lessen interruptions caused by left-turning traffic; the prohibition of on-street parking to minimize flow interruptions; and the establishment of a special lane for transit and high-occupancy vehicles to reduce the volume of traffic in noise-impacted areas.

Public Education Program

In developing nations, the level of public education and awareness concerning the adverse effects of transportation on the environment is very low. Inadequate and low-profile public education campaigns, a high rate of illiteracy (especially among older people), and a fairly recent experience with technology and mobility are among the factors contributing to this deficiency. A comprehensive educational program should aim at: improving driver behavior by discouraging the misuse of horns; increasing public awareness of air and noise pollution and its prevention; encouraging daily travel planning among family members to reduce travel demand; and promoting transit use and high-occupancy vehicle travel. The program should include a coordinated effort among all involved agencies and should extend to all segments of population.

SUMMARY AND CONCLUSIONS

The Kingdom of Saudi Arabia has recently experienced rates of socio-economic and infrastructural growth unparalleled in the history of the modern world. One particular result of increasing affluence has been the dramatic rise in the number of vehicles and a corresponding increase in urbanization and urban mobility. These developments have, in turn, led to noise and air impacts on the environment in the urban areas of the kingdom.

This paper reports on the findings of two ongoing funded research projects undertaken to analyze the noise and air impacts of transportation in Riyadh's urban environment. This information provides the necessary basis for the development of policy measures and actions required for the effective alleviation of the negative environmental impacts of urban transportation.

The findings indicated that traffic-generated noise and CO air pollution at heavily traveled roadways in Riyadh were high and exceeded permissible standards by a considerable margin.

The sample noise level measurements clearly showed that traffic noise intensity ranged from about 85 to 95 dBA. The results of a cumulative frequency distribution of noise levels showed that the intensities of the highest 10 percent (L_{10}) were very high at nearly all locations. The L_{10} is mainly affected by the frequency and the intensity of intruding single-event noises such as horns, sirens and heavy trucks.

The equivalent sound level (L_{eq}) ranged in value from a low of 81 dBA to a high of 91 dBA at the study sites. These high L_{eq} values point to the noisiness of the urban environment at these locations. This statement is further supported by high values of the traffic noise index and the noise pollution level. Both traffic volume and traffic speed demonstrated significant and positive correlations with various measures of traffic noise.

The maximum 1-hr and 8-hr mean CO levels exceeded the SAAQS of 35 and 9 ppm by a significant margin at all locations. The maximum 1-hr levels for the source centerline were 60, 40, and 51 ppm during 1985, and 59, 55, and 57 ppm during 1986, for the Al-Batha, Al-Jameah, and Al-Aseer arterials. The differences in mean CO levels for the two study periods were not statistically significant at the 95 percent level at either of the locations. The maximum 8-hr CO concentrations during 1986 were 21 ppm at the Al-Batha, 22 ppm at the Al-Jameah, and 14 ppm at the Al-Aseer roadways. Only about 1.5 ppm of these CO levels is contributed by sources (background) other than traffic in Riyadh.

Correlation analysis indicated that the variable of mean peak hour volume showed the highest degree of linear association with traffic CO. This was followed by wind velocity and traffic speed.

Five groups of mitigation approaches currently practiced in the developed nations are identified. These include source emission control, improved highway design and noise barriers, land use control, traffic management and transit promotion, and public education programs. The general applicability of these mitigation approaches is also discussed. Comprehensive and coordinated efforts will be required to minimize the adverse impacts of urban mobility on the environment.

Overall, it appears that rapid urbanization, increased mobility, and the favoring of private transportation by responsible authorities have combined to create a significant negative impact on the urban environment. As urbanization and auto ownership increase, the size and the complexity of the problems are likely to grow. Decision makers should make every effort to minimize these negative urban transportation by-products.

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Impacts of the Greenhouse Effect on Urban Transportation

William A. Hyman, Ted R. Miller, and J. Christopher Walker

Scientists suggest that temperatures might rise 5°F to 9°F over the next 100 years, and that the sea level could rise 2 to 5 ft in response. Temperature change might reduce snow and ice control costs, slow road and bridge deterioration, and eventually reduce required pavement thickness. The uncertainty of future temperatures suggests increasing the safety factor currently designed into expansion joints on bridges and major roads, and reexamining the heat tolerances of railroad tracks. A rising sea level and the potential for more intense storms could require bridge redesign, better airport drainage, and raising of low-lying streets near tidal waters. Retrofitting could be much more costly than changes made prospectively during reconstruction. Design standards and siting criteria should be reassessed in light of likely climate changes.

Two weather models developed for the Environmental Protection Agency (EPA) (*1*) suggest that the earth could be 5°F to 9°F warmer than today by 2080, warming as much in 100 years as it did since the last glacial period 18,000 years ago. The models suggest that since the Industrial Revolution began in 1850, enough carbon dioxide and pollutants were banked in the atmosphere to cause half that temperature rise. The rest would result from projected emissions over the next century. The emissions are raising the heat-reflectivity of the atmosphere, making the earth a considerably more powerful greenhouse. With an average temperature rise of 8°F, temperatures would rise 16°F at the poles, melting much ice. Sea level could easily rise 2 to 5 ft by 2080. Other weather-related effects might include increased evapotranspiration and storm and hurricane intensity (*2, 3*).

The heat wave of 1988, although not related to the greenhouse effect, vividly illustrates some of the potential temperature impacts. Hundred-degree weather distorted railroad tracks, forcing Amtrak to cut speeds from 125 to 80 mi/hr between Washington and Philadelphia (*4*) and possibly causing several train wrecks, most notably one that injured 160 people on a Chicago-Seattle run (*5*). Across the Midwest, record temperatures buckled highways (*6*). In the suburbs of Washington, D.C., steel expansion joints bubbled along a 13-mi stretch of I-66 (*7*). In Manhattan, extreme heat exacerbated the effects of long-standing leaks in 160 mi of concrete-sealed steam pipes that lie 11 ft below the streets, causing the asphalt to soften. As vehicles kneaded the asphalt, thousands of hummocks formed on city streets (*8*).

This article discusses the probable impacts of global climate change on urban transportation systems in Miami and Cleveland. In Miami, sea level rise could require investment of several hundred million dollars to raise streets and bridges and improve airport drainage. Costs could be similar in other low-lying cities with tidal waterfronts. In Cleveland and other inland or lake cities in cooler latitudes, the impact could be positive, with savings in snow and ice control costs, as well as in road construction and maintenance costs. The closing section of this article suggests that engineering standards related to roadway, bridge, and rail design may need revision in response to the potential for, and subsequently the reality of, global climate change.

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METHODS AND PRINCIPAL LIMITATIONS

This study was based on a critical review of existing infrastructure studies in Miami and Cleveland, discussions about likely impacts with local infrastructure experts, analyses undertaken by these experts, and calculations about probable impacts by the study authors. The analyses were preliminary. They revealed which infrastructure responses to global climate change might be expensive, but were not engineering analyses of the most cost-effective responses. Because detailed analysis was restricted to two cities, the study did not identify the full range of impacts that could arise across the country.

MIAMI

Miami is a hydrologic masterwork, a densely populated area bounded by water from below and on all sides. When the city was first developed, the entire southern tip of Florida was a mangrove swamp called the Everglades that often was awash in fresh water. The initial settlement was built on local high points of the Atlantic Coastal Ridge, 10 to 23 ft above sea level, and immediately adjacent to Biscayne Bay and the Atlantic Ocean. Today, most of Greater Miami is on lower ground made habitable through drainage and reclamation (*9*).

Just a few feet below Miami's surface lies the porous rock of the Biscayne aquifer, which is one of the world's most permeable. The seaward edge of the aquifer is flooded with salt water. Maps in the Dade County Comprehensive Plan show that the height of the water table varies about 3 ft between seasons, but always exceeds sea level in most of the aquifer. In the wet season, the water table is close to the surface except along the high points of the Atlantic Ridge.

As sea level rises, the pressure of the sea water will cause the sea to rush into the aquifer below the surface and push up the fresh water. A 3-ft rise in sea level would cause roughly an equal rise in the water table.

Streets and Highways

The City of Miami Department of Public Works reports that there are 756 mi of ground level streets within Miami. Lane miles total roughly 1,800. A typical city street consists of a 1.5-in. layer of asphalt constructed over an 8-in. limerock base. Beneath the base is a subgrade, with its top 6 in. compacted to a minimum of 95 percent of its maximum density. If the sea level and water table were to rise 2 to 5 ft, given the annual fluctuations in the water table and its proximity to the surface, the subgrade base of many city streets would be subject to a certain amount of saturation. This could cause complete structural failure if a heavy load were to pass over the surface. To prevent this, vulnerable streets would have to be raised.

The City of Miami Department of Public Works estimates that approximately 34 percent of street and highway mileage—257 mi—is 5 ft or less above the water table (D. Brenner, City of Miami Department of Public Works, personal communication, April 1988.). Raising streets by 3 ft during reconstruction, according to the Department of Public Works, would raise reconstruction cost from $150 to $175/linear ft with minimally improved transitions to adjacent properties. The cost is modest because fill can be surface-mined on public lands in the county.

The cost of reconstructing the 257 mi to adjust for a 3-ft rise in sea level would be $237 million. Omitted from this cost estimate are substantial private costs that would be incurred for better drainage, raising some yards (especially around newer buildings where the structure itself already is raised), raising lots at reconstruction, and pumping sewage from the houses to the mains in some areas.

Although the average temperature in Miami could rise from 75°F to 80°F, the increase should have negligible impact on streets and highways, because current asphalt pavement withstands substantial temperature variations, and pavement performance should improve as reconstruction incorporates technological changes.

Causeways and Bridges

The causeways running from Miami across Biscayne Bay to Miami Beach are between 5 and 10 ft above sea level and might risk structural weakening and failure. They would also be vulnerable because of the increased size of hurricane storm surges. These potential impacts could be avoided with reconstruction over the next 100 years involving design features to mitigate the effects of the sea level rise.

Except for steel drawbridges, most bridges in Miami are constructed of concrete and steel and have a life expectancy of 50 years in a saline environment. Only those near the coast have epoxy-coated reinforcing bars, a practice introduced in 1970 to fight corrosion. Without remedial action, the effects of sea level rise might include

- Pavement failure in low-elevation bridge approaches.
- Erosion beneath low-lying bridge abutments and consequent differential settlement, stresses, and strains.
- Potential lifting of corrugated steel and box culverts.
- A drop in the elevation of protective fenders on the piers over navigable waters.
- Reduced accessibility to low-lying bridges and causeways, inhibiting proper inspection and maintenance.
- Reduced underclearances on navigable waterways.
- Increased likelihood of flood backwaters, particularly for bridges over nonnavigable waters, which often have underclearances of 3 to 6 ft.
- Added slapping action of waves beneath some bridges.

Regardless of improvements over the next 100 years, bridges with piers and piles in both Biscayne Bay and in rivers would experience deeper scouring, but the decreased velocity in nonstorm conditions that results from increased water depth would mitigate the problem. Scouring would increase if storms became more frequent or severe.

The projected temperature increase should not cause bridge expansion outside design limits. Increased humidity, however, might accelerate paint deterioration on steel bridges in saline environments.

Airports

Miami International Airport is a major international hub. Located in northwest Miami, its airfields and aprons cover 7,000 a. Unlike the majority of major commercial airports, most of the surface area is asphalt pavement. The aprons are concrete. The asphalt varies in thickness from 2 to 17 in. depending on the base. Its extensive drainage system allows storm runoff to empty into ditches by the airfield, which in turn empty into the Blue Lagoon and the Tamiami Canal. The groundwater elevation ranges from 2 to 3 ft, runways 9 to 10 ft, and taxiways and aprons 8 to 9 ft. A 3-ft rise in groundwater would not flood the pavement or base, but would affect drainage retention capacity and exfiltration during a storm. If several large pumping stations were constructed to draw down the airport water table at the onset of a storm, acceptable operating conditions could be maintained. Drainage interconnections and related improvements such as pump stations, dikes and culverts might cost $30 million (R. Tripp, written communication to the Urban Institute, Howard Needles Tammen Bergendoff, 1988).

CLEVELAND

Cleveland could experience a marked change in climate over the next century. EPA's scenarios suggest that winter temperatures could increase 10°F, raising average temperatures above freezing. Summertime increases could range from 7°F to 12°F above the current 66°F average. Snowfall might be dramatically reduced, with average annual accumulations declining from 50 in. to about 8 in.

Conditions of Roads and Bridges

Like most cities, Cleveland maintains an extensive road and bridge network; it has some 1,550 mi of road and 93 bridges with a total surface area of 1.8 million ft^2 (*10*). By some measures, Cleveland's road and bridge stock is in poorer condition than is typical for U.S. cities. Among 34 cities with road condition data available for 1983, Cleveland ranked last in the percentage of road mileage rated as "good" (5.6 percent) as opposed to "fair" (91.8 percent) or "poor" (2.7 percent) (*11*).

Similarly, the city's bridges included on the federal bridge inventory are in relatively poor condition. Among 62 major U.S. metropolitan areas in 1980, the Cleveland area ranked 12th in its share of structurally deficient bridges: 23 percent of the area's 279 bridges fit this category. Among the 93 bridges for which the city has sole maintenance responsibility, 75 are structurally deficient by the FHWA definition (*11*).

The deteriorated state of the city's transportation infrastructure is the combined product of environmental and-budgetary factors (*12, 13*). Years of underfunded capital programs and deferred maintenance contributed to the need for major capital renewal. Nevertheless, engineers responsible for road and bridge design attribute a large share of the blame for poor road and pavement and bridge deck performance to environmental factors. These include moisture and temperature effects in the former case and the use of salt in deicing efforts in the latter.

Low-Temperature Effects on Pavement

The most serious low-temperature effect on flexible pavement (e.g., asphalt) performance is frost heaving, which occurs when free water in the roadbed soil collects and freezes to form ice "lenses" (*14*). The accumulation of thickness from these lenses causes localized heaving of the pavement surface during extended frozen periods. The principal variable affecting the amount of heave that occurs is the depth of frost penetration, which is directly correlated with the number of consecutive low-temperature days. The amount of heave, and hence the potential loss in serviceability, also is affected by the quality of drainage.

Currently, an average of 46 days annually have maximum temperatures below freezing. According to local highway engineers interviewed for this report, these subfreezing days, on average, produce about 5 to 6 deep freeze/thaw cycles annually. Under both climate change scenarios, the number of days below freezing, and hence the estimated number of cycles, will decline dramatically over the coming century. One scenario suggests a mean of 13 days annually with maximum temperatures below freezing, roughly a quarter of the total mean number of days currently. If the number of days below freezing are taken as a proxy of the number of freeze/thaw cycles to be expected per year, 75 percent fewer days below freezing produces an estimated 1.5 deep freeze cycles per year. City engineers estimated the current depth of frost penetration for bare pavement at 4 ft, with good drainage. Serviceability loss is estimated to be at most 0.75 psi, about 15 percent of the total index range. With increased mean temperatures, and based on a 75 percent decrease in days below freezing, a gain of 11 percent in psi (with a residual loss of 4 percent) is possible.

Frost heave is a very specific type of pavement damage attributable to climate effects. More general analyses of estimated stresses on pavement life using broad climatic regions produce similar results. The Moisture Accelerated Distress (MAD) index classifies subsoil and drainage types for geographic regions across the nation according to their potential for abetting "pavement distress" attributable to environmental factors (*15*). Pavement distress is observable in the cracking of flexible (largely asphalt) or rigid concrete pavements, frost heave of flexible pavements, or joint failure or spalling of rigid pavements.

The MAD index is based on the interaction of four factors: temperature, moisture, roadbed material, and drainage. The last two factors, as defined in the index, will be little affected by climate change. City highway engineers rate the typical subgrade in Cleveland as "moderately drained," and the granular layer as "free draining." Whatever improvement in drainage is attributable to lake level drop will not produce a shift in broad drainage categories.

The temperature and moisture changes attributable to global climate warming might produce winter conditions in Cleveland roughly akin to those prevailing today in Nashville, Tennessee (*16*). This would equate to a change in temperature zone, for purposes of calculating the MAD index, resulting in an approximate 7 percent decrease in potential for moisture-accelerated damage.

Another impact to be considered is design requirements for new or replacement road surfaces. Until 1986, The American Association of State Highway and Transportation Officials (AASHTO) defined a Regional Factor for use in the design of roadways using flexible pavements (*17*). This factor essentially was a summary measure of adverse weather conditions. It was used to weight the axle-load factor used to determine asphalt pavement thickness. This factor ranged from 0.5 in the far Southwest to a U.S. mean value of 1.7 to a maximum value of 3.5 in northern Minnesota. The Cleveland area value was 1.5. With an increase in mean temperature, and using Nashville as Cleveland's winter analogue, the value for Cleveland would drop from 1.5 to 1.0. This change suggests a 7.5 percent decline in the required thickness of asphalt overlays in roadway construction.

Maintenance Costs

Roughly estimated, the amounts to be saved in road and bridge repair costs as a result of decreased pavement and bridge deck stress are modest, but not negligible. Currently, Cleveland spends about $4.9 million per year on street repair, including filling potholes, cracks, and other surface defects. An additional $100,000 is expected on bridge deck repair (*10*). This amount is almost entirely devoted to routine pothole repair, filling of joint and other surface cracks, and other maintenance activities associated with routine treatment of ordinary surface wear and tear.

As seen in the preceding section, the change in the Present Serviceability Index attributable to frost heave is an estimated 7 percent. The estimated MAD index change, accounting for all sources of moisture-accelerated distress including frost heave, is 11 percent. If these changes are correlated with actual incidence of pavement damage, then a conservative estimate of annual savings attributable to reduced damage frequency is roughly 10 percent or $490,000.

The city performs only emergency repair on bridges. City engineers indicate that of an average annual bridge maintenance budget of about $1 million, about 10 percent is expended on the repair of bridge decks, the remainder supporting maintenance of lift bridge mechanisms (*12*). Although some deterioration of bridge decks can be attributed to the effects of temperature and moisture alone, these effects are minimal compared with the use of road salts. Because milder winters mean sharply reduced snow and ice control efforts, far less corrosive salt will need to be spread on the area's bridges. Nevertheless, the authors judge that negligible economic benefit will be credited to this development because of improved winter maintenance practices over time. Also, since 1970, widespread use of epoxy-coated reinforcing steel as a means of preventing contact between the bare steel and deicing salts should reduce corrosive impacts long before milder winters become the norm (*18*).

Capital Costs

AASHTO design guidelines, including the regional factors used in the flexible pavement design equation, are a good means of estimating changes in capital costs attributable to climate change. The expected change in winter temperatures, using an analogue of Nashville, Tennessee, means a reduction in the AASHTO Regional Factor from 1.5 to 1.0. Each unit change in the Regional Factor produces a 13 percent change in the structural number, and therefore the thickness, of flexible pavement (*17*). For roadway construction or reconstruction jobs, roughly 26 percent of total construction costs are attributable to pavement costs. Of this figure, 70 percent of costs are variable with thickness. Therefore, 18 percent of total construction costs are potentially affected by weather (26 percent × 70 percent). Thus, a change in the Regional Factor from 1.5 to 1.0 on roadway reconstruction jobs means a drop in total costs of approximately 1 percent.

Resurfacing jobs, however, contain a higher percentage of pavement costs to total job cost than do reconstruction jobs—approximately 60 percent. Using the 70 percent of costs that are variable with thickness, as before, 42 percent of total resurfacing costs can be viewed as weather influenced. If a 0.5 drop in the Regional Factor means a 7.5 percent change in structural number, then total cost reductions on resurfacing work are estimated at 3 percent.

Table 1 presents Cleveland's road resurfacing and reconstruction costs for 1983–87. Assuming that the city's capital investment levels by category change proportionately over time and that the climate-adjustment factors are approximately correct, a 5-year estimated savings of about $1 million can be expected on a total budget of $76 million.

Snow and Ice Control Costs

As in many other Northeastern cities, snow removal operations in Cleveland receive high priority from city administrators and agencies during the winter months. The Division of Streets, responsible both for roadway maintenance and snow removal, maintains four stations throughout the city during summer months. Two are manned at three shifts per day, one at two shifts, and one at one shift. These stations primarily perform street sweeping and repair. During winter months, however, six stations are activated, all manned at three shifts per day and all engaged primarily in snow and ice removal. Limited street repairs are undertaken throughout the winter months. The personnel used in city snow removal operations all are city employees and the equipment consists of Division of Streets vehicles.

Ordinarily, at the onset of snow or ice precipitation, the city will salt streets using employees and equipment assigned to their regular shifts. At this stage, some 45 units will be employed in salt spreading. If snow accumulates at ½ in./hr, or if a 2-in. accumulation is reached, the second shift will be called 4 hr early, while the first shift will be kept on 4 hr overtime. This brings total equipment on the road to 81 salt and plow units, and 15 graders. Typically, for any storm between 4 and 12 in. over a 12-hr period, the city will average 50 to 75 vehicles for the first 12 hr, and 95 to 100 over the second 12 hr. In addition to drivers, foremen and mechanics responsible for vehicle maintenance work similar shift patterns.

The annual cost of removing snow consists principally of labor costs attributable to snow removal activity, and the cost of expendable materials, such as salt, used in deicing. Table

TABLE 1 CLEVELAND ROAD RESURFACING AND RECONSTRUCTION OUTLAYS 1983–1987

Year	Reconstruction	Resurfacing	Climate-Savings
1983	$ 5,184	$1,930	$110
1984	6,233	2,179	127
1985	5,334	2,391	124
1986	26,544	2,166	330
1987	21,913	2,166[a]	284
Total	$65,208	$10,832	$977

[a]Estimated. Climate change savings are computed as 1 percent of reconstruction costs, 3 percent of resurfacing costs.
NOTE: Dollars in thousands.
SOURCE: Compiled by the Urban Institute based on unpublished material supplied by the City of Cleveland Budget Office (1987 figures) and data from the Mayor's Estimates, 1983–1986.

TABLE 2 SNOW AND ICE CONTROL COSTS

Year	Cost ($, in thousands)	Accumulation (in.)
1980	3,477	38.7
1981	4,282	60.5
1982	5,646	100.5
1983	4,069	38.0
1984	5,379	79.4
5-yr average	4,571	63.4

SOURCE: City of Cleveland Mayor's Estimates, various years; and U.S. Climatic Research Center.

2 presents Cleveland's annual snow removal budget for recent years, and the associated inches of accumulation. As the table shows, removal costs roughly track total accumulation.

The average amount of snow accumulation projected for Cleveland under each climate change scenario is about 8 in. per year, a mere 16 percent of the current annual average. The winter comparable for the Cleveland area, Nashville, Tennessee, registers average annual snow accumulation in amounts roughly equal to those projected for Cleveland. Nashville snow removal costs from 1982 to 1987 averaged about $200,000 per year. Data from other cities confirm that Nashville's approximate level of expenditure is an appropriate benchmark for accumulation of that magnitude.

These data imply that Cleveland's snow removal budget could decline from its current annual average of $4.6 million per year to about $200,000 per year. The decline of 95 percent, for an annual savings of $4.4 million, represents about 1.9 percent of the city's $235 million operating budget.

Transit

The Greater Cleveland Regional Transit Authority (RTA) operates a fleet of 1,022 vehicles carrying over 88 million passengers per year. The fleet includes 815 buses, 91 light railcars, and 116 heavy rail cars.

Analysis does not suggest any significant impact on RTA capital costs because of climate change. Neither the rail nor the bus fleets now have special equipment mandated by snow conditions that could be eliminated (and thus save costs) in subsequent replacements. All vehicles are equipped with heating systems, which still will be needed as winters become milder. All rail cars have two 7-ton air conditioning units. These should have adequate capacity to handle much longer hot weather seasons and RTA staff suggest that, if anything, a more regular use would probably improve their operation because lubricants would circulate more effectively.

None of the Cleveland buses are presently air conditioned, so equipment would probably have to be added in this category at some time over the coming century. Given an estimated average 10- to 14-year replacement cycle and considering the expected pace of temperature increases, however, there would be no justification for accelerating replacements on these grounds alone. Also, the American Public Transit Association indicates that most buses now being sold are equipped with air conditioning and that the percentage continues to increase. Price differentials for buses with and without such equipment are already small and are narrowing. Therefore, it appears that adding air conditioning for Cleveland area buses during regular bus replacement cycles over the next century would not have a noticeable effect on total capital outlays.

Similarly, although climate change will alter RTA operating costs, our interviews suggested that all effects will probably be too small to warrant quantification. On the one hand, heavy snow accumulations at present do create problems, particularly for the rail system. Snowflakes that work their way into power systems can produce "flashes" (shorts) that demobilize the equipment and yield large repair bills. RTA will be able to reduce allocations for snow clearing and other outlays for prevention/correction as snow diminishes in the future. On the other hand, some increase in fuel consumption is likely to result from more frequent use of air conditioning equipment. Rail widths also may have to be reduced slightly at replacement to reduce the chance that speeds might need to be restricted on very hot days. In relation to the overall size of RTA's $126 million expense budget for 1987, effects will be small.

IMPLICATIONS

Roads

For the most part, temperature change could reduce the cost of road construction and maintenance. Snow and ice control costs will drop dramatically. In Cleveland the costs could drop by 95 percent, almost $4.5 million per year. In cities like Washington, D.C., they might drop to zero. A decrease in deep freezes and freeze-thaw cycles also would mean fewer potholes. Warmer temperatures and the improved drainage resulting from higher evaporation rates could allow use of thinner subbases, bases and pavements in many areas, but require enhanced expansion capabilities. The savings in Cleveland are likely to be 1 percent of road reconstruction costs and 3 percent of resurfacing costs, about $200,000 per year, plus 10 percent of maintenance costs, about $500,000 per year. The reconstruction and resurfacing cost savings only will be realized if pavement standards are adjusted to reflect climatic conditions as they change.

Bridges

Sea level rise and increased storm intensity could require many bridges to be upgraded, either through retrofitting or as part of normal reconstruction, and make it harder to defer needed improvements. The range of temperature accommodated by expansion joints also might need to be increased in some areas.

Mass Transit

The impacts on transit should be modest and largely concentrated on operating costs. In the North, buses and rail cars could experience fewer snow-related delays. Conversely, slight increases in fuel costs could result from increased use of air conditioners. High-speed rail track also might need replacement to accommodate hotter temperatures.

Airports

Some airports might need enhanced drainage capacity. Air operations might face more summer disruptions because of summer fog and thunderstorms. Conversely, winter disruptions attributable to snow and ice could drop substantially.

CONCLUSIONS

The uncertain, yet potentially imminent impact of global climate change already has increased the riskiness of infrastructure investment. Application of design standards and extrapolation from historical data might not still provide reasonable assurance that expansion joints, bridge underclearances, or drainage will be adequate during a 20-, 50-, or 100-year design life. The National Flood Insurance Program's historically based maps identifying the 100-year floodplain and 500-year floodway might no longer provide a reliable basis for roadway siting. Because of increases in storm intensity that may accompany climate change, historical data might not be an adequate basis for decisions about the cost-effectiveness of wind shear radar at airports. And migration in response to climate change could radically alter the population growth projections underlying capacity decisions about highway and airport systems.

Corporate investment analysts have developed methods, including decision theory, portfolio analysis, and chance-constrained programming, to guide decision making under uncertainty. Infrastructure analysts at all levels of government might be wise to adapt these methods to their work. Especially in coastal areas, the possibility of accelerating global climate change soon may require careful decisions about how and when to adapt the infrastructure. A strong emphasis on life-cycle costing and the courage to make expensive upgrades during reconstruction in anticipation of future changes could provide large cost savings.

Growing uncertainty about future temperature, precipitation, and sea levels might dictate a reassessment of existing standards and safety factors for drainage, flood protection, facility siting, underclearances, thermal expansion capacity, and resistance to corrosion. Conversely, prompt detection of lasting changes could allow adjustment of geographically based standards—for example, on roadbed depth—and provide significant savings.

AASHTO, the American Society of Civil Engineers (ASCE), the American Society for Testing and Materials (ASTM) and the Transportation Research Board (TRB) should consider educating their committees about global climate change. The decisions of these committees on when and how to incorporate climate change into their analyses and recommendations, especially when the recommendations vary geographically, could have major cost implications. The Strategic Highway Research Program (SHRP) might be well advised to consider climate change in developing its material and performance specifications and pavement monitoring plans. As part of its needs assessment process, FHWA also might be wise to assess the potential impacts of global climate change on the Federal-Aid Highway System. Raising bridges and increasing thermal expansion capacity prospectively during reconstruction might be more cost-effective than risking sea level rise.

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Aerial Structure Noise Reduction Effectiveness of Resilient Rail Fasteners

JAMES T. NELSON

Resilient rail fasteners have received significant attention at the New York City Transit Authority (NYCTA) and the Washington Metropolitan Area Transit Authority (WMATA) as a means for reducing wayside noise from steel stringer and steel box elevated structures and groundborne noise from subways. Noise and vibration data collected at NYCTA and WMATA indicate that noise and vibration reductions are generally small unless very soft resilient fasteners are used. Very soft fasteners providing good low-frequency performance may exhibit poor isolation or amplify structure vibration at frequencies above 200 to 400 Hz because of resonances in the elastomer pad or top plate. Laboratory tests of the forward transfer impedance of resilient rail fasteners indicate that these secondary resonance frequencies are about 600 to 800 Hz for the softest fasteners tested for the NYCTA and WMATA systems. A laboratory test procedure has been developed into an acceptance test procedure for resilient fasteners supplied to the WMATA system as noise-reducing fasteners for either subway or elevated structure use. This procedure represents a substantial change in acceptance test procedures that have heretofore focused on physical properties related to stability and safety of the fasteners. Data are presented illustrating measured noise reductions and laboratory test results.

Resilient rail fasteners have received significant attention for controlling elevated structure noise and groundborne noise and vibration from subways. Early work included field measurements and evaluation of prototype fasteners for the San Francisco Bay Area Rapid Transit System (BART) (*1*). Field tests were conducted by the Toronto Transit Commission (TTC) at the Yonge Subway Northern Extension tunnels to determine the effect of fastener stiffness reduction on groundborne noise (*2*). The New York City Transit Authority (NYCTA) has completed testing and evaluation of several candidate rail fasteners for use on steel elevated structures (*3*). There have been notable contributions in the area of predicting wayside noise and vibration. These include a review of various prediction methods for steel elevated structure (*4*), and a detailed prediction method (*5*) that includes an effect attributable to rail fastener elastomer standing wave resonances.

This paper discusses some of the noise control results obtained at the Washington Metropolitan Area Transit Authority (WMATA) Metro with resilient direct fixation rail fasteners at a section of a steel box concrete deck aerial structure. Results for the NYCTA solid web steel stringer and wood tie deck elevated structures (*3*) are not yet available for publication. A laboratory test procedure was developed for evaluating the effective stiffness of resilient fasteners for frequencies extending up to at least 1000 Hz. The procedure has since been developed into a laboratory acceptance test for procurement of resilient noise reducing fasteners at WMATA. A discussion of the procedure is provided.

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WAYSIDE NOISE AND VIBRATION FROM ELEVATED STRUCTURES

Wayside 1/3 octave band noise levels measured at 1.5 m above grade near two elevated structures are presented in Figure 1. The first spectrum is of noise produced by WMATA Metro trains traveling at approximately 60–70 km/hr on a concrete deck steel box aerial structure with sound barrier wall. The second is of wayside noise produced by 40 km/hr Chicago Transit Authority (CTA) trains on a wood tie deck solid web steel stringer elevated structure. Both spectra exhibit a general roll-off above about 500 Hz. The noise from the CTA structure exceeds that from the WMATA structure by 5 to 15 dB above 125 Hz. Below 63 Hz, the radiation efficiency of the CTA solid web steel stringer decreases with decreasing frequency, relative to that of the WMATA steel box, producing a large disparity between low-frequency noise levels for these two basic structural configurations.

Our experience at the NYCTA suggests that virtually the entire spectrum shown for the CTA elevated structure is attributable to stringer-radiated noise, though Remington's (1985) prediction model suggests that the wood tie deck is also a significant source. For solid web steel stringers, the wayside *A*-weighted noise levels are determined by the broad peak at about 500 Hz. Resilient rail fasteners selected for reducing stringer vibration and radiated noise at steel elevated structures must, therefore, be effective beyond 500 Hz, placing significant demands on fastener design.

Figure 2 illustrates the vibration reduction effectiveness of three relatively soft resilient rail fasteners field tested at the WMATA system. These include the LORD #79, the Clouth Cologne Egg, and the Advanced Track Dual-Stiffness Egg, with dynamic stiffnesses of 18 MN/m, 14 MN/m, and 9 MN/m, respectively. The vibration reductions are relative to vibration measured for the standard WMATA fastener, and were obtained by measuring steel box girder vibration at the bottom and sides before and after installation of each of the fasteners. The data are thus good comparisons of fastener performance in reducing structural vibration.

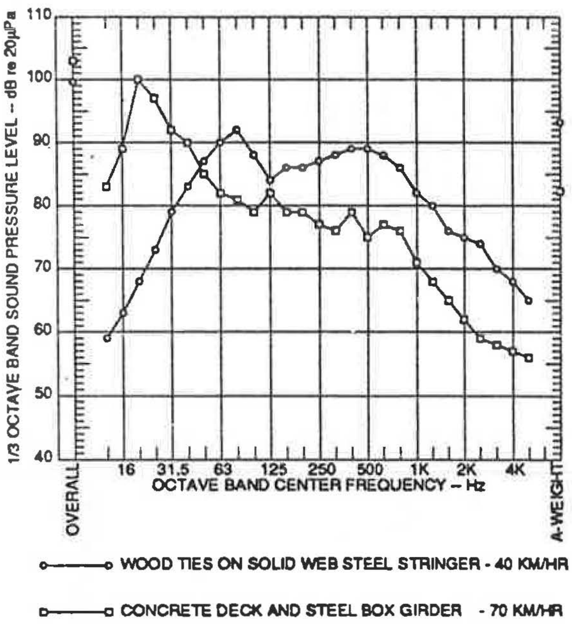

FIGURE 1 Aerial structure noise at 1.5 meters above grade.

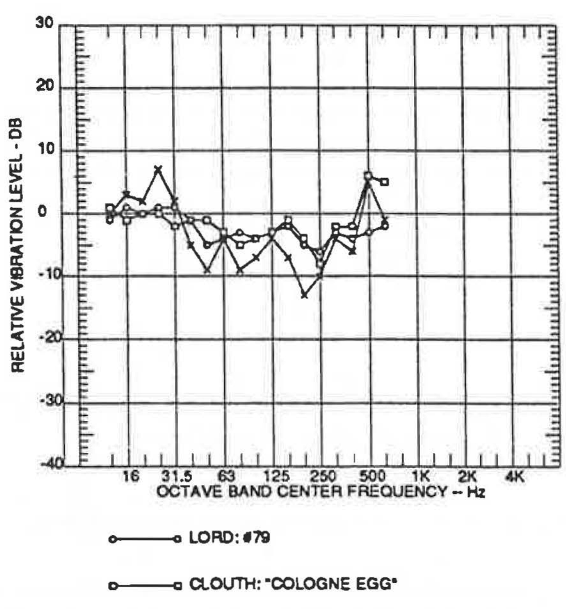

FIGURE 2 Vibration reductions relative to standard WMATA fastener.

The results given in Figure 2 indicate that all of the soft fasteners produced significant vibration reductions from 63 Hz to about 315 or 400 Hz; the Dual-Stiffness Egg provided the greatest vibration reduction. At 25 Hz, some amplification of vibration with the Dual-Stiffness Egg may occur relative to the standard WMATA fastener. Both the LORD 79 and Clouth Egg give essentially similar results. The low-frequency behavior of the various track fasteners is well predicted by a model of an elastically supported rail and unsprung wheel set mass with a prescribed wheel/rail roughness (*6*).

Little or no vibration reductions were obtained at 500 Hz. Because this is an important frequency for steel elevated structures, characterizing fasteners at these frequencies and attempting to understand why a fastener may or may not be effective at high frequencies is important.

LABORATORY TEST PROCEDURE

A laboratory test procedure has been developed for studying the high-frequency vibration isolation effectiveness of resilient rail fasteners. The test determines the forward transfer impedance of a fastener under representative static loads. The forward transfer impedance is the ratio of the Fourier transforms of the transmitted vertical force to the rail web vertical velocity with baseplate blocked. The test, therefore, includes the effect of rail flange and fastener top-plate bending.

Figure 3 is a schematic of the test apparatus. The machine is supported on pneumatic springs, and weighs approximately 680 kg. The base is solid steel, weighing approximately 550 kg, and exhibits a fundamental vibration mode at about 1200 Hz. The fastener is bolted to a 1.9-cm thick aluminum plate and placed on a flat load cell that integrates the transmitted force over the load cell area. A short section of rail is placed in the fastener, with an accelerometer mounted in the plane of the rail web. A second accelerometer is mounted beneath the inertia base to provide an inertial reference signal that can be used to extend the low-frequency range of the test. Static loads are applied to the rail and fastener assembly with pneumatic springs. The fastener's forward transfer impedance is measured by tapping the top of the rail and measuring the transfer function between transmitted force and rail web velocity with a dual-channel Fast Fourier Transform (FFT) analyzer.

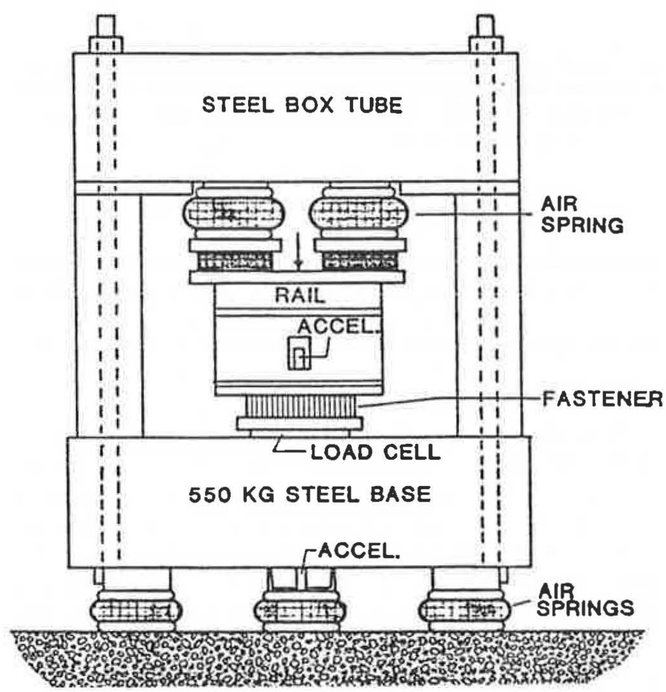

FIGURE 3 Resilient rail fastener test apparatus.

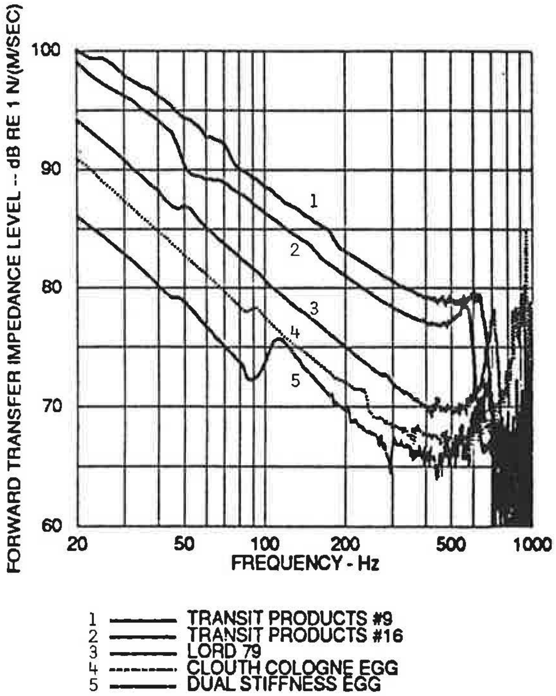

FIGURE 4 Comparison of various fasteners under 13 KN static load.

Forward transfer impedance functions for various fasteners are presented in Figure 4. Represented are two WMATA TW-10 prototype fasteners manufactured by Transit Products, Inc. (TPI #9 and #10) and three "soft" fasteners: LORD #79, Couth Cologne Egg, and the Advanced Track Dual-Stiffness Egg. The two WMATA TW-10 prototype fasteners are substantially stiffer than the soft fasteners, as indicated by their high transfer impedance magnitude levels. The Dual-Stiffness Egg exhibits the lowest dynamic stiffness over the entire frequency range shown, consistent with the results of Figure 2.

Most of the fasteners exhibit a spring-like characteristic up to about 200 or 300 Hz. The Dual-Stiffness Egg, however, exhibits a resonance at about 100 to 125 Hz, probably because of the elastomer suspended beneath the top plate. Above 300 Hz, the forward transfer impedance functions deviate significantly from a "spring-like" characteristic. The TW-10 prototypes exhibit resonance peaks at about 570 Hz and 600 Hz, and the remaining fasteners exhibit peaks at about 700 Hz. The forward transfer impedance of the Dual-Stiffness Egg is given in Figure 5 for a series of static loads. At low static load, the resonance frequency for the Dual-Stiffness Egg drops significantly to about 630 Hz. This was observed for the Clouth Egg also. At high static loads, the dynamic stiffness of the Dual-Stiffness Egg rises, eventually exceeding those of the LORD #79 and Clouth Fasteners.

The measured steel box girder vibration reductions illustrated in Figure 2 are minimal at about 125 Hz, and some amplification is evident at 500 Hz. The low isolation at 125 Hz observed for the Dual-Stiffness Egg may be related to the resonance at about 125 Hz observed in its forward transfer impedance. The resonance at about 620 Hz observed for the Clouth and Dual-Stiffness Eggs at low static load may explain the slight amplification of structural vibration at 500 Hz. More testing is desirable to verify these relationships.

FASTENER TOP PLATE BENDING

Figure 6 illustrates the theoretical forward transfer impedances of two fasteners idealized as uniform steel plates supported on elastic foundations. One of the plates is 1.27 cm thick, supported on an elastic foundation giving a total static stiffness of 25 MN/m. The second curve is of a 1.905-cm thick steel plate supported on an elastic foundation giving a total

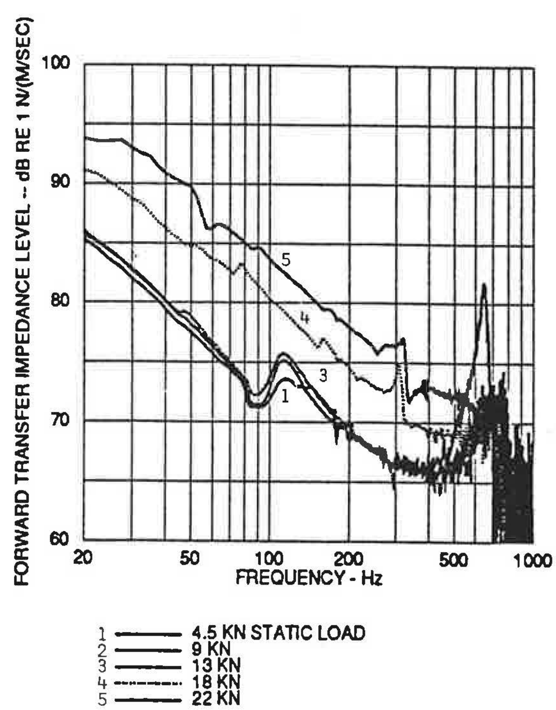

FIGURE 5 Dual stiffness egg forward transfer impedance.

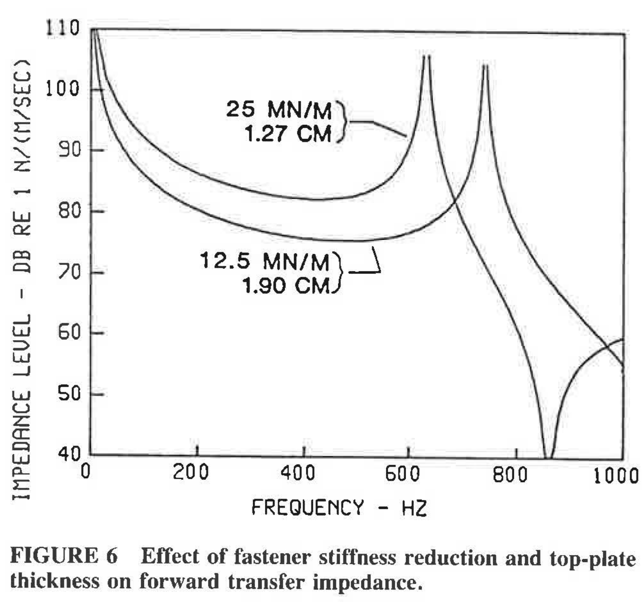

FIGURE 6 Effect of fastener stiffness reduction and top-plate thickness on forward transfer impedance.

static stiffness of 12.5 MN/m. Top-plate dimensions are 30.48 cm by 17.78 cm. The lower stiffness represented by the forward transfer impedance of the "soft" fastener would not have been obtained above 500 Hz if the top plate thickness were not increased. Without thickening the top plate, the peak in the forward transfer impedance would have been about 550 Hz.

The ratio of dynamic-to-static stiffnesses of the fasteners are also influenced by bending of the plate. At low frequencies, top-plate bending reduces total fastener stiffness relative to that obtained by rigid body deflection of the top plate. At the resonance frequency associated with the top-plate mass on the elastomer, the top-plate motion is rigid, resulting in increased dynamic stiffness relative to the low-frequency case. Thus, fasteners should be designed with as rigid a top plate as practicable to reduce the ratio of dynamic-to-static stiffness at audio frequencies, and maintain the frequency of the forward transfer impedance peak as high as possible, preferably about 1000 Hz. Rail flange stiffness contributes to top-plate stiffness, and use of heavy rail should be favorable to lightweight rail.

CONCLUSION

The experience gained at WMATA indicates that elevated structure noise can be reduced by selecting resilient rail fasteners of stiffness 9 MN/m to 18 MN/m. Effective performance over the most significant frequency range of wayside noise, however, requires that top-plate bending resonance frequencies be maintained as high as possible, preferably in excess of 1000 Hz. Stiffening the top plates will also lower the ratio of dynamic-to-static stiffness, desirable for elevated structure noise control.

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