Allocating Pollution Costs Using Noise Equivalency Factors

L. R. RILETT

Noise pollution associated with roadway traffic and methods of reducing its negative impacts has been a research issue for over 30 years. One of the more popular approaches to reducing noise pollution has been to install noise barriers along the sections of roadway where noise levels exceed some acceptable standard. The cost of these barriers, however, is usually borne by the transportation authorities and not those who directly cause the problem. With the advent of ITS, and electronic toll pricing in particular, there exists a unique opportunity to recover the costs of noise pollution directly from the people who produce it. The focus of this paper will be to identify methods by which the financial cost of noise pollution may be equitably allocated to those vehicles that cause the noise. The first section of the paper will briefly examine different types of cost allocation methodologies. Subsequently, the methods by which noise pollution is quantified and predicted will be explored and discussed. The concept of noise equivalency factors will be introduced and used to calculate a responsibility measure for different vehicle classes. Lastly, a simple example will be used to outline the concepts developed in the paper.

With the recent advances in ITS, particularly in the areas of electronic toll collection, there has been renewed interest in demand management techniques such as peak hour pricing to reduce congestion in urban areas. There also has been a significant amount of interest on the part of both the driving and nondriving public to reduce the level of pollutants emitted from vehicles. One of the proposed methods of achieving both of these aims is to set the electronic toll prices to capture not only congestion costs but also pollution costs. Consequently, there is a requirement to identify the level of responsibility of each vehicle type in order to set the pricing strategy in a fair and equitable manner.

It is the intent of this author to demonstrate some of the potential methods for allocating pollution costs in situations in which those responsible can be identified and their relative levels of responsibility can be assessed. Noise pollution only is examined in this paper although the techniques can be applied to any type of pollution. The section on cost allocation techniques (below) examines typical cost allocation techniques and identifies the methods most appropriate for highway transportation agencies. The section on sound and noise gives a brief overview of traffic noise, and the section on noise equivalency factors (NEF) illustrates approximate NEF for various vehicle types using the concepts discussed in the previous sections.

COST ALLOCATION TECHNIQUES

Within the field of highway agency cost allocation there is currently much debate over the appropriate methodology for allocating costs. Traditionally highway agencies have attempted to recoup their financial outlays through some type of average cost strategy in which the principle debate consists of defining the most "equitable" manner of doing this. More recently marginal cost pricing has been touted as the more economically efficient and therefore more desirable strategy. The problems with this approach include the high probability of excessive administration costs and the fact that many highway projects are not based solely on economic criterion, which means that the full cost of the project might not be recovered. Perhaps more importantly, from an implementation standpoint, is that there is no consensus on what the marginal cost would be. For example, it is easy to argue that if highway pavement thickness were designed for the expected environmental conditions and the expected truck traffic (which it is in Canada), then the marginal cost of the pavement thickness for automobiles is effectively zero. Conversely, if it is argued that the roads are built solely for automobile usage, then the marginal cost to trucks for the additional pavement is relatively low (*1*). In either case, a marginal cost strategy would be unacceptable both to the trucking firms in the former case and to the automobile associations in the latter case. For these reasons highway agencies have tended to use some type of equitable, as opposed to efficient, cost allocation strategy, as discussed in the next few paragraphs.

Public policy makers are primarily interested in the equitable allocation of highway costs in order to ensure that taxes (or user charges) are fair and that, ideally, they recoup their expenditures. Typically it is direct agency costs such as pavement construction and maintenance that are analyzed. In this paper a technique for allocating the agency costs of traffic noise pollution will be examined. These agency costs will only involve the capital cost of noise attenuation barriers, although the concepts may be used for other costs as well.

Highway agency expenditures may be classified as belonging to three distinct categories for cost allocation purposes. The first types are known as uniquely occasioned costs or long term separable costs. These are costs that may clearly be assigned to one vehicle class. An example of this would be truck weigh stations. The second types are known as common costs and these are costs that may not reasonably be assigned to one vehicle class. The cost of land acquisition for roadway right-of-way is an example of a common cost. Lastly, there are joint costs in which all vehicle types have some responsibly, but this responsibility varies by vehicle type. An example of this is pavement costs, which all vehicle user classes are responsible for incurring, although obviously with differing levels of responsibility. It will be shown in subsequent sections that the agency costs of traffic noise fall into this category.

Once the costs have been identified they have to be allocated or assigned to the different vehicle classes. Traditionally there have been three equity concepts that may be used as a basis for highway

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Department of Civil Engineering, University of Alberta, Edmonton, Alberta, Canada, T6G 2G7.

cost allocation (*2*). The first is the received benefit equity concept, in which user charges are proportional to the benefits received by the users. The second is the occasioned cost equity concept, in which the users are charged in proportion to the cost for which they are directly responsible. Lastly, there is the ability to pay equity concept, in which the users are charged in proportion to their ability to pay.

Most highway agencies have adopted the occasioned cost concept, whereby the users are assigned the average costs that are expended by the highway agency for each of their trips. The challenge in this technique is to identify a suitable responsibility measure that captures the occasioned costs and that may allow the joint costs to be allocated to the different vehicle classes. For highway pavements, it has been shown that a suitable responsibility measure is the load equivalency factor (*1*). In this paper the focus will be on developing a similar responsibility measure for traffic noise.

SOUND AND NOISE

The problem of vehicle and traffic noise associated with traffic networks has been gradually gaining public attention over the past 40 years. Although not as great an issue in North America as in Europe (which has a much larger population density), it is still one of the most easily recognized environmental disbenefits associated with automobile transportation (*3*).

Traffic Noise

The sound pressure and the sound pressure level (*4*) are easily measured and calculated and may be used to categorize traffic noise quantitatively. However, the effects of noise on the auditory systems of human beings are a little more complex, and consequently traffic noise is usually defined in a subjective manner. Sound may be ordered on a scale from soft to loud, and from this the "loudness" of a sound may be derived. Loudness depends not only on the sound pressure level but also on the frequency and wave form of the stimulus. Sound meters used in traffic noise measurement identify only the actual sound pressures of a traffic stream and not the subjective loudness rating. For this reason they are equipped with internationally defined weighting filters that attempt to translate the sound pressure level into measurements of the subjective sound level. The sound level is defined in decibels. There are three standard weighting factors, but the A range is generally used for traffic applications, and it has been shown to have a reasonable correlation with objectively determined rankings (*5*).

Although the unit of noise is relatively easy to define, other subjective measures associated with noise also need to be quantified. For example, as the flow and traffic composition on the roadway changes, the noise level also changes. There are a number of common methods of quantifying the variability of the resulting noise. One measure is the mean sound interval (L_n), which is defined as the mean sound level exceeded n percent of the time. Various values of n have been used to quantify noise, with the most common being 10, 50, and 90 percent. The equivalent sound unit (L_{eq}) was developed in Sweden. It is effectively an average noise level that equates the actual noise to the same A weighted sound energy over the same period of time. The formula used to calculate the equivalent sound unit is indicated in Equation 1 (*6*).

$$L_{eq} = 10 \log_{10}\left(\frac{1}{100}\sum_{i=1}^{n} f_i \, 10^{l_i \; 10}\right) \tag{1}$$

where

l_i = the sound level corresponding to the midpoint of class i;
f_i = the time interval for which the sound level is in the limits of class i; and
n = the number of classes.

Traffic Noise Prediction Methods

There are many traffic noise prediction models that are used worldwide. These models are used primarily for assessing the potential noise levels for new roadways or noise levels in the future because of traffic increases. The majority are based on empirical measurements and have been extensively calibrated and validated. This paper will focus on a model that is used in the province of Ontario, although the procedures adopted will be applicable to any model.

The FHWA traffic noise prediction model, STAMINA, is one of the more widely used models in North America, and has been used by the Ontario Ministry of Transportation for traffic-related noise studies (*6*). The central feature of the model is the use of reference noise emission levels for various classes of vehicles that use the traffic network. These reference levels are subsequently adjusted for particular situations. In the general case, the vehicle stream is assumed to be composed of three vehicle types: automobiles, medium trucks, and heavy trucks. Medium trucks are defined as two-axle vehicles which generally weigh less than 5500 kg and typically have a pickup or van body type. Any truck that exceeds these minimum standards is considered a heavy truck.

The actual noise level at any point varies with many factors. For instance, traffic volume, percentage trucks, average speed, distance to highway, shape of road, ground cover, height of roadway, height of receiver, as well as environmental factors (wind, etc.) all may be important. Based on these inputs and the FHWA equations, the total hourly equivalent sound level $L_{eq}(h)$ in $dB(A)$ may be calculated for actual or forecast conditions.

Ontario has developed a simplified method of predicting traffic-related free field noise in $L_{eq}(h)$, based on a modified version of the STAMINA model (*7*). Although the model is not as complicated as the original STAMINA program, it does give some general insight into traffic noise. The predicted noise level is a function of traffic volume, equivalent distance to the roadway, ground cover coefficient, and equivalent subtending angle. The general relationship is indicated in Equation 2.

$$L_{eq} = 10 \log\left[\frac{\Phi}{15} VK\left(\frac{15}{D_E}\right)^{1+\alpha}\right] \tag{2}$$

where

V = volume of traffic (veh/h);
K = parameter representing effect of different vehicle classes;
D_E = equivalent lane distance [average distance to nearest and furthest lane (m)];
ϕ = equivalent subtending angle; and
α = site parameter (land-dampening coefficient).

The parameter ϕ is the equivalent subtending angle and is used to model the decrease in noise level caused by intermediate obstructions. When the place at which the sound level is being estimated is unobstructed, the noise emanating along the entire roadway needs to be accounted for. In this situation ϕ may be found by using Equation 3.

$$\Phi = \frac{180}{1 + .58\alpha^{0.9}} \tag{3}$$

In the modified STAMINA model the energy emission models for each vehicle type are combined into a direct energy expression. This combination is defined as K in Equation 2. K may be calculated using Equation 4.

$$K = K_A + K_{MT} + K_{HT}$$

$$K_A = \frac{N_A}{442.53V} S_A^{2.81}$$

$$K_{MT} = \frac{N_{MT}}{5.83V} S_{MT}^{2.39}$$

$$K_{HT} = \frac{N_{HT}}{3.59721 \cdot 10^{-2}V} S_{HT}^{1.46} \tag{4}$$

where

N_A = number of automobiles on roadway (veh/h);
N_{MT} = number of medium trucks (veh/h);
N_{HT} = number of heavy trucks (veh/h);
V = total volume of vehicles (veh/h);
S_A = average speed of automobiles (km/h);
S_{MT} = average speed of medium trucks (km/h); and
S_{HT} = average speed of heavy trucks (km/h).

It may be observed in Equation 2 that the volume parameter V occurs in both the numerator and denominator (through the K factor) and hence may be canceled out. The volume is thus represented explicitly by the number of automobiles, medium trucks, and heavy trucks. It may be observed that as the number of vehicles increases so does the value of L_{eq}. It should be noted that an increase of X automobiles would lead to a smaller increase in noise than would an increase of X heavy trucks. That is, a heavy truck will cause more traffic noise than an automobile, all other factors being equal. This last point will be examined further in the next section.

NEF

It is clear from Equation 4 that the different vehicle classes are responsible for differing amounts of the estimated noise. That is, the responsibility of traffic noise pollution cannot be deemed the sole responsibility of one vehicle class and consequently an individual vehicle for one vehicle class will contribute a different amount to the total noise produced than an individual vehicle from another vehicle class. As discussed in the section on cost allocation techniques, a responsibility measure is required in order to allocate joint costs based on the occasioned cost methodology. In this section a method for developing NEF for the various vehicle classes will be illustrated.

The Load Equivalency Factor (LEF) is used in highway design to assess the impact of a heterogeneous traffic stream on the pavement. The basic technique is to reduce the truck load damage to an equivalent number of passes of a standard load: the so-called ESAL (equivalent single axle load). Therefore, any vehicle may be defined as a fraction or multiple of the ESAL by means of a LEF. As an example, a truck with a LEF of 1.5 would cause 1.5 times the damage of a standard ESAL. In effect, the LEF is used to transform a heterogeneous measure (vehicles in a traffic stream) to a homogeneous one (number of ESALS in a traffic stream) in order to facilitate the design process. The concept of a NEF is similar to the LEF. In this case a standard vehicle is chosen, and the NEF represents the number of standard vehicles a particular vehicle would be equivalent to with respect to noise production. As an example, a truck with a NEF of 10 indicates that the truck produces the same amount of noise as 10 standard vehicles.

If it is assumed that the automobile is the standard vehicle, then the NEF for a heavy truck (denoted here as $NEF_{HT\text{-}A}$) may be calculated using Equation 5. It may be observed that the $NEF_{HT\text{-}A}$ is simply the ratio of the derivative of the L_{eq} function with respect to the number of heavy trucks and the derivative of the L_{eq} function with respect to the number of automobiles.

$$NEF_{HT-A} \frac{dL_{eq}\,(N_A, N_{MT}, N_{HT})}{dN_A} = \frac{dL_{eq}\,(N_A, N_{MT}, N_{HT})}{dN_{HT}} \tag{5}$$

If the traffic noise production follows that of the modified STAMINA model, the resulting $NEF_{HT\text{-}A}$ is indicated in Equation 6 below.

$$NEF_{HT-A} = 12{,}302 \frac{S_{HT}^{1.46}}{S_A^{2.81}} \tag{6}$$

In summary, Equation 6 identifies the number of automobiles that would give rise to the same increase in traffic noise as that caused by the addition of one heavy truck for a given set of roadway conditions. The large value of the constant implies a relatively high trade-off between cars and heavy trucks with respect to noise responsibility, all other things being equal. However, the NEF will tend to decrease with an increase in average speed, as evidenced by the relative difference in the exponents of the speed parameters. It is important to note that for this example only the ratio of the vehicle classes has an effect on the NEF and not the traffic volume. The volume will, of course, affect the estimated L_{eq} value. A similar procedure may be used to derive the NEF between medium trucks and automobiles, as indicated in Equation 7. The NEF between heavy trucks and medium trucks may be found in the same manner and is indicated in Equation 8.

$$NEF_{MT-A} = 75.85 \frac{S_{MT}^{2.39}}{S_A^{2.81}} \tag{7}$$

$$NEF_{HT-MT} = 162.185 \frac{S_{HT}^{1.46}}{S_{MT}^{2.39}} \tag{8}$$

Assuming that all the vehicle types travel at the same speed, Figure 1 may be developed from the above equation, which indicates the different NEF as a function of the average speed on the roadway. It can be observed that at a speed of 50 km/h, one heavy truck is responsible for the same amount of noise as approximately 63 automobiles. This ratio decreases with increasing speed and at 100

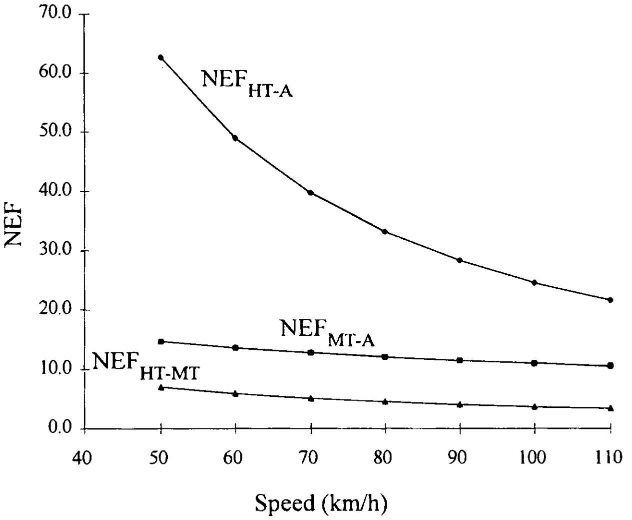

FIGURE 1 NEFs from the modified stamina model.

km/h it may be observed that 25 cars are equivalent to one heavy truck. The NEF for medium trucks as compared to automobiles ranges from approximately 2 to 16. The relatively large constant in Equation 8 would appear to imply that there is a large difference in truck noise accounted for by heavy as opposed to medium trucks. However, the relationship between the speed parameters is such that for realistic situations, the NEF varies from about 5 to 2, as indicated in Figure 1.

As stated previously, the above technique could be used to calculate NEF from other noise prediction models as well. For example, a noise prediction model for arterial roadways that operate with speeds in the range of 10 to 60 km/h has been developed (*8*). Heavy trucks were defined as trucks weighing over 1525 kg. The NEF (again using the automobile as the standard vehicle) for heavy trucks and medium trucks for this model are calculated as 13 and 9, respectively. These values are very different from those indicated in Figure 2. Two points need to be addressed. It is impossible to simply compare the parameters of two models without an in-depth study of the data collection, assumptions, definitions, and techniques used to create the models. It is not the intent of this author to identify the best NEFs, but rather to identify the technique used to calculate them. Secondly, the NEF is calculated so that it may be used in the cost allocation process. The following sections will illustrate how the NEF may be used to allocate noise barrier costs. An example of the cost allocation technique for a noise barrier will be performed along with a sensitivity analysis to illustrate the effect that different NEF values will have on the results.

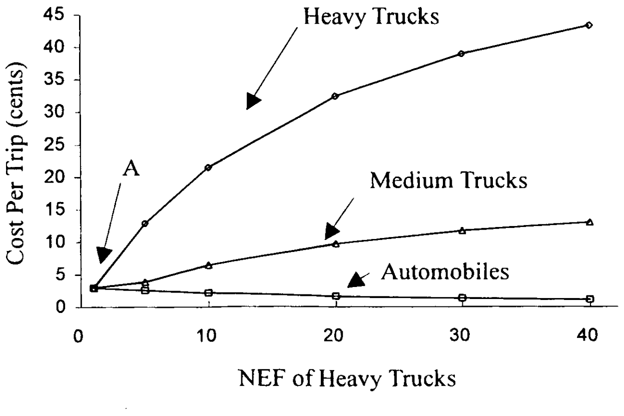

FIGURE 2 Sensitivity analysis of example problem (3 percent heavy trucks, 5 percent medium trucks).

Allocation of Noise Barrier Costs

As discussed in the section on cost allocation techniques, highway agencies have typically used the occasioned cost principle to allocate the construction, maintenance, and operating costs of their facilities. In the remainder of this section, an examination of how the costs associated with noise barriers may be allocated to the different vehicle classes that use the traffic network will be presented. It should be kept in mind that although this analysis pertains to noise pollution, the principles and techniques would apply to any negative externality.

A number of additional items need to be addressed at this point. The first is the matter of economic rights with regard to who is ultimately responsible for the cost of noise mitigation: the homeowners who are affected by the noise or the vehicle owners who produce the noise. Typically, if a noise barrier is being constructed in a developed residential area, the cost is absorbed by the transportation agency, which collects its monies through various taxation schemes. The decision of whether to construct a noise barrier is based on established guidelines, and these guidelines relate to the measured noise levels in the area. For example, in Edmonton, Alberta, once the noise level reaches 65 dBA, a community is eligible for a noise barrier. In new residential areas, the decision to build a noise barrier depends on projected noise levels, for both the base and future years, which are calculated using noise prediction models, as discussed in the section on cost allocation techniques. The cost is absorbed by the developer, who subsequently passes the cost onto the homeowner in the purchase price of the lots. In this paper it is assumed that the noise barrier is being built in a developed area and the transportation agency wishes to recoup the cost directly from the drivers who cause the noise instead of from general revenues.

The second point concerns the manner in which a cost recovery scheme could be implemented. Until recently this exercise would have been more of an academic exercise because it would have been infeasible to charge vehicles on a per use basis. However, with the advent of electronic toll pricing, noise barrier costs may be easily recouped on a per use basis. In this paper the responsibility measures used will be the NEF, as discussed earlier. Therefore, the costs will be allocated on a vehicle class basis in which each vehicle is classified according to the definition of the STAMINA model.

Lastly, it should be kept in mind that this paper is seeking only to demonstrate the procedure instead of attempting to define the optimal pricing strategy. For example, it may be hypothesized that in actual practice each vehicle would be tested annually to determine the various emission levels of different types of pollution (hydrocarbons, noise, etc.). From these measurements the equivalency factors could be calculated for each individual vehicle. These equivalency factors could then be used to price roadway trips according to criteria such as how much pollution they produce, where they produce it, and when they produce it. In areas that currently undergo such testing, the additional cost would be minimal. This scheme would have the desirable feature of allowing vehicle owners to explicitly trade-off the costs of vehicle improvements (i.e., quieter tires) versus the increased cost of electronic tolls associated with not investing in noise attenuation improvements. If time-of-day pricing were instituted, it may also have the effect of spreading the peak pollution periods. Regardless, the analysis in the next section will give an approximate estimate of the allocated costs to each vehicle type, which may be useful in determining whether current pricing techniques are equitable for all vehicle classes.

Sample Problem

The following is an example of how the NEF concept may be used to allocate the cost of a noise attenuation barrier. Consider an arterial roadway where a noise barrier has been constructed along both sides in order to reduce the noise to an acceptable level during the peak periods. The cost of this barrier is approximately $1,000 per m, which results in a total project cost of $1 million. If the project life is assumed to be 20 years and a real interest rate of 4 percent prevails, the transportation agency would have to recover $73,581 dollars per year in order to recoup the construction costs.

During the morning and afternoon peak periods (1-h length), the hourly flow is 4,800 vehicles per hour, which is composed of 92 percent automobiles, 5 percent medium trucks, and 3 percent heavy trucks. If it is assumed that there are 260 days in a year when the acceptable noise level is exceeded, then there are approximately 2.5 million vehicles per year that should be charged the cost of the noise barrier. If the agency charged all vehicles the same then the cost per vehicle to use this section of road would be 2.95 cents ($73,581/2,496,000) per trip. Note that travelers during the off-peak times would not be charged, as they are not responsible for the noise that makes the noise attenuation barrier necessary.

If the transportation agency decided to recover the capital cost of the barrier based on the occasioned cost principle with the NEF used as the responsibility measure, then the toll prices would be somewhat different. If the average speed on the arterial is 70 km/h, the NEF for the three vehicle classes would be 1, 12.7, and 39.7, respectively, as indicated in Figure 1. This implies that the noise caused by the current peak hour traffic stream would be equivalent to that produced by approximately 6.85 million cars—2,496,000 [1(0.92) + 12.7(0.05) + 39.7(0.03)]. The cost per automobile would decrease to 1.1 cents per trip, the cost per medium truck would increase to 13.6 cents per trip, and the cost per heavy truck would increase to 42.6 cents per trip. This pricing strategy would result in the heavy trucks paying approximately 40 percent and medium trucks paying approximately 20 percent of the capital cost of the noise barrier.

Of course, the results of the above example are based on all of the assumptions of the example problem, in particular the NEF values. Figure 2 illustrates a sensitivity analysis of the NEF values. The x-axis represents the NEF for heavy trucks. It is assumed that a NEF ratio 1-12-40 applies for the different vehicle classes such that a NEF for heavy trucks of 20 implies a NEF for medium trucks of 6. The y-axis represents the cost per trip for the different vehicle classes that would have to be charged in order to recover the cost of the noise barriers.

Point A in Figure 2 represents the situation in which all vehicles are charged the same rate (i.e., both heavy trucks and medium trucks have a NEF of 1). As would be expected, as the NEF for heavy trucks increases so too does the cost per trip for the trucks, whereas the cost per trip for automobiles declines. Note that the slope of all of the curves depends not only on the NEF but also on the number of vehicles in each vehicle class. At a NEF of 10 the heavy trucks would pay a relatively high cost of 20 cents per trip, which is still significantly higher than the average vehicle cost method. Under this pricing strategy the heavy trucks would pay approximately 25 percent of the cost of the noise barrier and the medium trucks approximately 5 percent.

The example problem was subsequently analyzed when the percentage of trucks doubled with all other factors being held equal. The graph of this scenario is indicated in Figure 3. Point A in Figure 3 represents the cost per trip when all vehicles are charged at the same rate. The cost per trip for this scenario is the same as in Figure 2 because the volume on the roadway has not changed. It may be observed in Figure 3 that the cost per trip for all vehicle types decreases when the percentage of trucks increases. The reason for this is that although the cost responsibility of the trucks increases there are now more of them, leading to a decrease in the average cost per trip. For example, at a LEF of 40 the cost of the barrier paid by automobile users drops from approximately 40 percent in the first scenario to 25 percent in the second scenario.

CONCLUDING REMARKS

It was not the intent of this author to provide a definitive answer to the question of cost allocation of noise pollution to the different vehicle classes. Rather, the objective was to provide insight into some of the issues involved and to demonstrate some of the more promising techniques for setting pricing strategies for pollution. However, a number of interesting points have been illustrated in this paper.

It is possible to use the existing traffic noise prediction models, such as the modified STAMINA model, to assign responsibility to the different vehicle classes as long as the models explicitly account for the effects of each vehicle class on the noise level. Based on the modified STAMINA traffic noise prediction model, it was shown that the relative responsibility levels or NEF for trucks was much higher than for automobiles. As an example, it was illustrated that at a speed of 100 km/h one heavy truck was equivalent in noise responsibility to 25 automobiles whereas one medium truck was equivalent to 11 automobiles. Although the original noise prediction models were not developed for cost allocation purposes, the

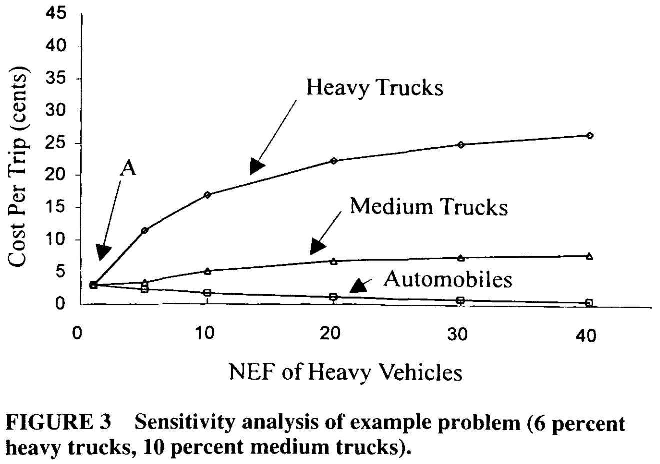

FIGURE 3 Sensitivity analysis of example problem (6 percent heavy trucks, 10 percent medium trucks).

fact that they have been used extensively in numerous noise studies provides some validity to the results. However, as illustrated in the section on NEFs, different noise prediction models can provide different results, and it is currently unclear which model (and hence NEF) is the most appropriate to use.

Once the relative responsibility measures or NEF have been identified, they may be used to allocate pollution costs to the various vehicle types. It was shown in a relatively simple example that the actual amount allocated to each vehicle in this method could be significantly different from that achieved by allocating the cost simply on a per vehicle basis. For example, when the cost was allocated in the sample problem on a per vehicle basis, the cost of a noise attenuation barrier was approximately 3 cents per trip. However, when the cost was allocated on a standard vehicle basis using a NEF of 10 for heavy trucks, the cost per trip for heavy trucks increased to approximately 20 cents per trip. It was shown that the actual charge for a particular vehicle type depends on many factors including the number of vehicles, the percentage of trucks, and the responsibility measure used.

Although the concepts developed in this paper are relatively straightforward, there are a number of further questions that also need research attention. In particular, what are the optimal NEFs for cost allocation procedures? What are the equivalency factors for other pollution costs? Could a cost recovery system based on the occasioned cost principles be implemented given the recent advances in electronic toll collection techniques? Lastly, and perhaps most importantly, if such a cost recovery system were implemented, what would be the implications in terms of system users reducing their noise production by buying quieter cars, driving slower, changing their routes, or driving during different periods of the day? These questions will form the basis of further research on this topic.

ACKNOWLEDGMENTS

Funding for this project was supplied by the Natural Science and Engineering Research Council of Canada and is gratefully acknowledged. The author would also like to thank the referees of this paper for their thoughtful and useful comments.

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Publication of this paper sponsored by Committee on Transportation Economics.