University of Alberta

Measures of Responsibility for Noise and Air Pollution and Their Application in Road Pricing

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled Measures of Responsibility for Noise and Air Pollution and Their Application in Road Pricing submitted by David Christopher Jordan in partial fulfillment of the requirements for the degree of Master of Science. in Transportation Engineering.

Dr. Laurence R. Rilett

Dr. Stan Teply

Dr. Gordon R. Finch

Dr. John D. Whittaker

June 6, 1996

To My Parents
for love, guidance and support

Abstract

The concept of road pricing has been forwarded as a possible solution to the problems of traffic congestion, noise pollution, and air quality degradation in urban areas. This thesis investigates the issues involved in allocating the costs of noise and air pollution to those responsible for these problems and using engineering models as a basis for measuring responsibility. In order to be equitably implemented, the charges assessed in a road pricing scheme should be based on the costs occasioned by the individual vehicles. Measures of responsibility of vehicles for noise and air pollution are derived in the form of equivalency factors for different vehicle classes. These equivalency factors are calculated from widely-used empirical prediction models. Although discrepancies exist within the vehicle classes themselves, heavy trucks are shown to bear the costs of air and noise pollution far more than automobiles. A illustrative example is used to show the possible application of equivalency factors in road pricing schemes.

Acknowledgment

This research would have been impossible without the help and support of the following people, among others. Dr. Laurence Rilett was instrumental as an advisor, partner in research, and friend. Dr. Stan Teply, Dr. Gordon Finch and Dr. John Whittaker provided valuable criticism and commentary as part of my defense committee. I must also thank Dr. Teply along with Dr. William Sproule for inspiring me as an undergraduate student to pursue graduate studies in transportation engineering. At Texas A&M University, Charles Bell, Amy Stephenson, and Dr. George Dresser took extra time to assist me with the finer details of air quality research. I thank my parents for leading by example and for giving me many second chances. Finally, I am grateful to Hilary Neatby, without whose sacrifices I would not have been able to realize my potential.

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Table of Contents

List of Tables

List of Figures

CHAPTER 5

Chapter 1

Introduction

1.0 Overview

Sustainable development has been defined as, "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (Our Common Future, 1987). This thesis suggests that the ability of future generations to meet their needs is jeopardized by the depletion of three resources: clean air, quiet, and road space. Clean air is essential to a healthy and satisfying quality of life. Although a risk-free urban atmosphere is impossible to attain, it is clear that the public desires a reduction in the current level of air pollution in urban areas. Strict air quality legislation has been passed in areas of high pollution in North America and transportation projects have been halted on the basis on public concerns about the risks of both air pollution and noise. A certain level of quiet is associated with a satisfactory quality of life. When quiet is replaced with traffic noise, stress and annoya[illegible]s well, road space is essential for accessibility to urban activities. The increased use of road space has resulted in congestion delays for the households who are dependent on automobiles for their mobility. All three of these resources are impacted by the increasing amount of single-occupant motor vehicle traffic in urban areas.

Road pricing has been forwarded as a way of stemming the overuse of these resources. Road pricing is a Direct Demand Management technique that involves charging individual road users for their share of the overall levels of noise, air pollution, and congestion in urban areas. The advent of certain Intelligent Transportation System (ITS) innovations, including automatic vehicle identification (AVI) and electronic toll collection (ETC) technologies, make it possible to charge drivers for their contribution to these problems. By changing the costs directly perceived by drivers through road pricing, metropolitan transportation authorities may be able to meet environmental objectives more effectively than with capacity improvements or indirect demand management policies alone.

This thesis assumes that for road pricing to be effectively implemented, the concept of equity must be incorporated into the allocation of costs to vehicle operators. Road user charges should reflect the fact that different vehicles contribute to overall noise and air pollution levels to varying degrees. Such charges also may entail a transition from the use of traditional tax revenue sources to fund the construction, operation and maintenance of transportation facilities. In a successful road pricing scheme, the charges assessed to vehicle operators will be based on the principles of equitable cost allocation as they are applied in other engineering endeavors.

1.1 Objectives of this Thesis

Road pricing has been forwarded as a sound method of attending to the overuse of quiet, clean air and road space. AVI and ETC technologies have advanced to the point that the implementation of road pricing as described above is now possible. The objective of this thesis is to develop an equitable method of allocating the costs of motor vehicle noise and air pollution within a road pricing scheme.

Allocating these costs among different vehicle classes necessitates the derivation of measures of responsibility for noise and air pollution in urban areas. This in turn demands prior knowledge of the principles of noise and air pollution and their generation by motor vehicles. The goals of this thesis, then, are:

1. To investigate the issues involved in equitable cost allocation,

2. To present an overview of the fundamentals of road pricing and motor vehicle noise and air pollution,

3. To investigate the factors influencing and the methods of predicting the generation of noise and air pollution by motor vehicles,

4. To derive measures of responsibility of different vehicle classes for air and noise pollution, and

5. To demonstrate how these measures might be applied in road pricing schemes.

1.2 Approach to Meeting the Objectives

Chapter 2 presents an overview of road pricing and the reasons for linking road user charges with the generation of noise and air pollution. An investigation of different equity concepts is presented as part of a discussion of the economic theory of road pricing in Chapter 3. Several of these concepts are extended from the existing theory of cost allocation in pavements to the allocation of the costs of noise and air pollution in road pricing. A method of determining the responsibility of different vehicle classes for overall levels of noise and air pollution is developed.

The literature review also serves as a starting point for the investigation of motor vehicle noise and air pollution in Chapters 4 and 5, respectively. Measures of responsibility for noise are derived from ten traffic noise prediction models in the form of an Equivalency Factor for Noise, or EF_N. Similarly, measures of responsibility for air pollution are derived from the MOBILE5 air quality model in the form of an Equivalency Factor for Air Pollutants, or EF_p. At the end of each chapter, a illustrative example is used to demonstrate the application of the Equivalency Factors in road pricing.

1.3 Scope of the Analysis

As discussed above, the costs of noise and air pollution are allocated in this thesis on the basis of the contribution of different vehicles to overall pollution levels. This approach is applied to widely-used models of traffic noise and air quality. Ten traffic noise prediction models from North America and Europe are used to calculate EF_N's. The MOBILE5 air quality model, used extensively throughout North America, is used to calculate the EF_p's. These models have their limitations as discussed in Chapters 4 and 5. Variation in noise and air pollution generation between the classes of vehicles is discussed, as is the importance of emissions other than hydrocarbons, carbon monoxide, and nitrogen oxides, the pollutants the MOBILE5 model is capable of predicting.

Although the topic of road pricing is introduced in the thesis, there is no detailed investigation of how vehicle operators' economic choices would be affected by new charges. Furthermore, the barriers to the implementation of road pricing are only briefly discussed.

The analysis in this thesis focuses on the relative levels of responsibility of different vehicle classes for noise and air pollution. The quantification of the costs of the overuse of clean air and quiet is discussed, but these costs are not estimated. Instead, in the hypothetical road pricing scenario presented in Chapters 4 and 5, the relative charges that would be assessed to different vehicle classes are presented.

1.4 Organization of this Thesis

Chapter 2 presents an overview of road pricing, a method of incorporating the costs of noise, air pollution, and travel delay into the decisions made by individual travellers in urban areas. Chapter 3 presents a review of the literature in five areas: road pricing, equity in road pricing and cost allocation, motor vehicle noise pollution, motor vehicle air pollution, and the assessment the costs of air and noise pollution. Chapter 4 introduces the methodology by which measures of responsibility for pollution are determined. Equivalency Factors for noise, or EF_N's, are calculated using this methodology. The EF_N's derived from ten traffic noise prediction models are applied in a hypothetical road pricing scheme. In Chapter 5, the same methodology is applied to the MOBILE5 emission model to derive Equivalency Factors for different pollutants, or EF_p's. The sample problem used in Chapter 4 is revisited to illustrate the use of the EF_p in road pricing schemes. Finally, in Chapter 6, conclusions are drawn from the literature review and the subsequent analysis and a series of recommendations are forwarded.

Chapter 2

An Overview of Road Pricing

2.0 Introduction

This chapter presents the arguments forwarded in support of road pricing. Section 2.1 describes the phrase, "Tragedy of the Commons," and shows how it applies as a metaphor in urban road use. Specific trends in urban form and transportation choices are forwarded as evidence of the overuse of clean air, quiet and road space. In Section 2.2, four different approaches to the problems of congestion and increasing air and noise pollution are introduced: *infrastructure* capacity improvements, *traffic management* capacity improvements, *indirect* demand management, and Direct Demand Management. These approaches are examined in terms of their impact on the overuse of clean air, quiet and road space in urban areas. The remainder of Section 2.2 draws from this investigation in concluding that Direct Demand Management has potential to reverse the trends toward a tragedy of the urban commons, and that road pricing is the most equitable form of Direct Demand Management.

2.1 The Overuse of Clean Air, Quiet and Road Space

"The Tragedy of the Commons," is an expression often used to describe the overexploitation of resources (Stevenson, 1991). The phrase refers to a specific scenario: a herdsman is putting animals out to pasture on the commons, land that is owned by the state (Garrett, 1968). If the herdsman adds one more animal to his grazing herd, he can reap the rewards of selling the animal in the future. There are costs to all of the other herdsman that are using the commons, of course. To the one herdsman adding the animal to his herd, the cost is a fraction of the benefit that he will gain from the sale of the animal. The herdsman considers adding yet another animal to the herd, and even though the supply of grass is dwindling in the fields, putting the animal out to graze results in great benefits. Each herdsman makes the same decision again and again. The fields may be decimated, but each herdsman still benefits from putting more animals out to pasture. The unlimited access each herdsman has to the fields results in their overuse (Stevenson, 1991).

Likewise, a traveller in an urban area must make certain decisions: whether or not to make a trip, where to go, what mode of travel to use, and what route to take. Like the herdsman adding an animal to the pasture, the traveller does not usually consider the air and noise pollution created. The risk she bears from her own vehicle's emissions is minute compared to the benefit she gains from driving alone. However, when one million travellers use the same decision criteria in the same urban area, the risks to all users in the area grow.

Just as the commons are decimated by overgrazing in the herdsman's scenario, the urban air and noise pollution problem has become a contentious issue in urban areas throughout the world today. In the United States, the threat of withheld funding through the provisions of the Clean Air Act Amendments of 1990 (CAAA) and the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) has made it imperative for metropolitan planning organizations to stem the growth in motor vehicle emissions (Stephenson and Dresser, 1993). As well, despite the fact that the pollutants emitted by individual vehicles have been reduced by almost 90% in the past 25 years, air quality standards continue to be exceeded. Noise pollution is often cited as the greatest complaint of residents in urban areas, and is responsible for annoyance, health affects related to stress, and various affects on social activities (Alexandre et al., 1975). As well, the level of congestion experienced in most US urban areas has been steadily increasing (Schrank et al., 1995). These indicators suggest that three resources, clean air, quiet, and road space, are being overused in many urban areas.

Other trends suggest that, like the herdsmen on the verge of decimating their field, North American travellers show no signs of abating their use of these three resources. In general, the average use of transit in urban areas continues to decline from World War II levels, while the average density of urban areas is also declining (Rothenberg, 1992). This suggests that people are living further away from their activities in part due to the mobility offered by the automobile. Figure 2-1 relates the short term travel decisions to these long term trends, which are essentially long term decisions made by individual urban residents, into a framework. Note that there are two categories of choices people make that affect travel demand: long-term activity pattern choices and short-term mobility choices.

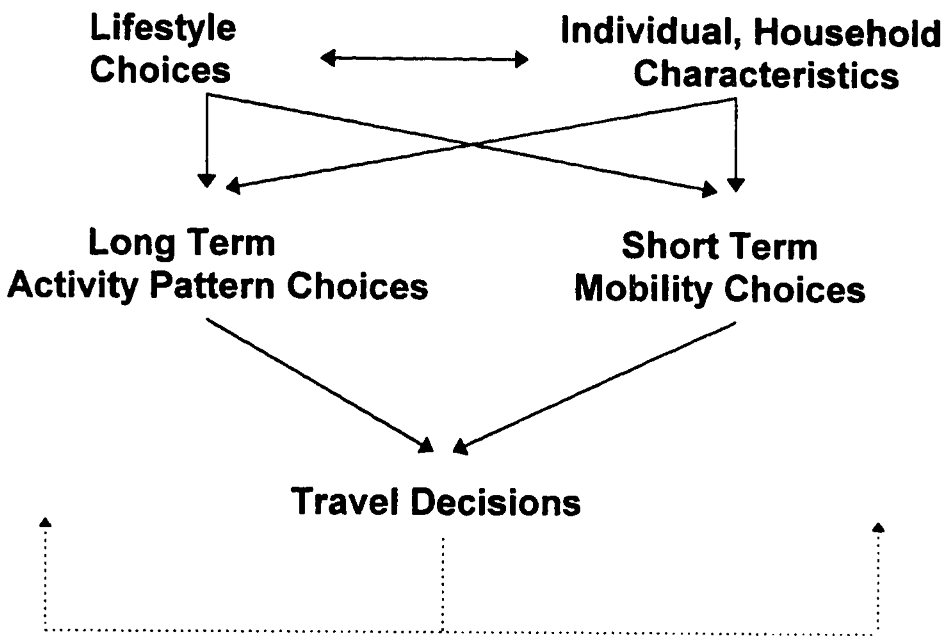

Figure 2-1. Short Term and Long Term Decisions in Urban Areas

Furthermore, aggregate travel demand increases as an urban area's population increases. The carrying capacity of the road network is increased where possible to accommodate this demand. Three trends, then, are outlined: short-term mobility choices, long-term activity patterns, and urban growth. These three trends are often shown interrelated in the land use cycle shown in Figure 2-2.

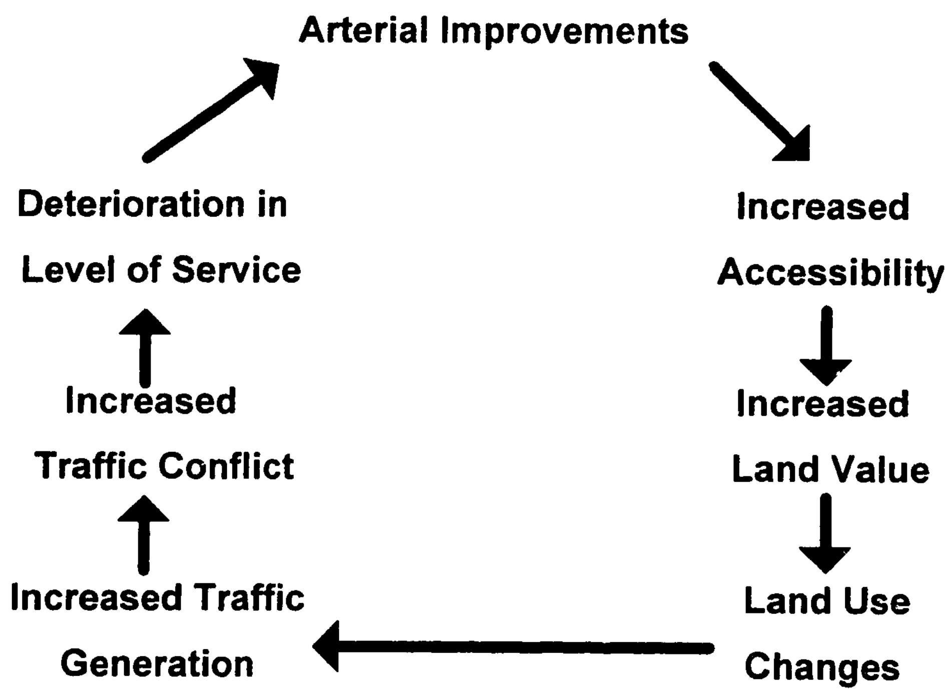

Figure 2-2. The Land Use Cycle (source: Edwards, 1992)

An increase in the motor vehicle accessibility of a destination makes it attractive for the traveller to drive. The resultant increase in traffic produces conflicts between vehicles in the road network. The usual remedy, increasing the capacity of the road network, continues the cycle. This remedy has the same effect as expanding the commons bit by bit to accommodate more animals. As discussed in Section 2.2, this initially permits more use of road space, but actually adds to the overuse of the two other resources, clean air and quiet.

Clearly, individual drivers do not factor the costs of air and noise pollution into their decisions to live further from work, to drive alone, and to drive in congested traffic conditions. Just as the herdsman gains from putting an animal to pasture even if it can only find a bit of grass, the driver gains from putting up with the frustration of congestion. The user of the common facility exacts costs on other users, but does not factor these costs into the decision to use the facility, in one case, the pasture and in the other case, the road network.

Currently motorists are not charged on the basis of their use of clean air, quiet, and road space. These three resources are valued to varying degrees by the general public, particularly in residential areas. There are no property values assessed to clean air and quiet; as a result, they may be considered common property. Drivers do not perceive the full costs of using these resources. As they fill clean air with pollutants, they impose costs on non-drivers who depend on being able to breath clean air. As vehicles emit noise, costs are imposed on people that depend on a quiet environment for their quality of life. These costs vary from place to place and from time to time. They are not taken into account by motorists making decisions on whether or not to make a trip, where to go, how to travel, and how to get there. Unless they feel remorse because they are responsible for these external costs, or externalities, travellers will make their decisions regardless of the severity or extent of external effects. The difference between perceived costs and actual costs involved in the decision to drive can be explained with the help of Figure 2-3 (Lewis, 1993). The decision to drive can be written as a function of the cost of congestion borne by all road users, or average variable cost. The benefits that the road user derives from the trip can be defined as marginal benefits, or the increase in benefits for each additional journey. The intersection of the two curves below represents a point of equilibrium, where the average cost of driving on the network is equal to the benefit derived from the trip.

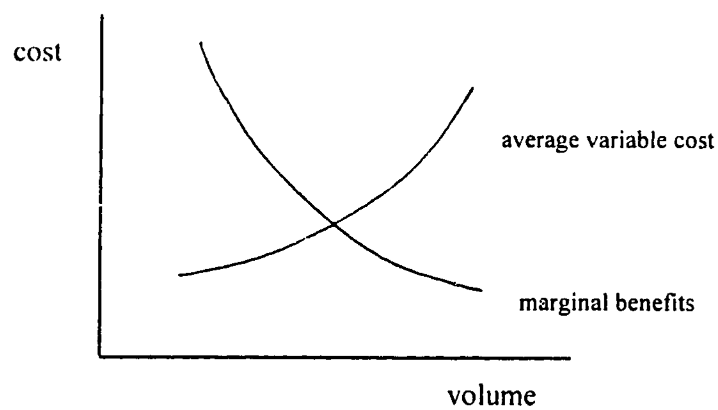

Figure 2-3. Perceived Equilibrium Between Marginal Benefits and Average Costs of Driving (Source: Lewis, 1993)

Two curves must be added to this chart to illustrate how the road users' perception of costs creates problems. The marginal private cost is defined as the perceived cost of any additional trip to the driver. The marginal social cost is defined as the sum of external effects of the additional trip, where external effects include congestion, air pollution and noise. These are placed on the chart as shown in Figure 2-4.

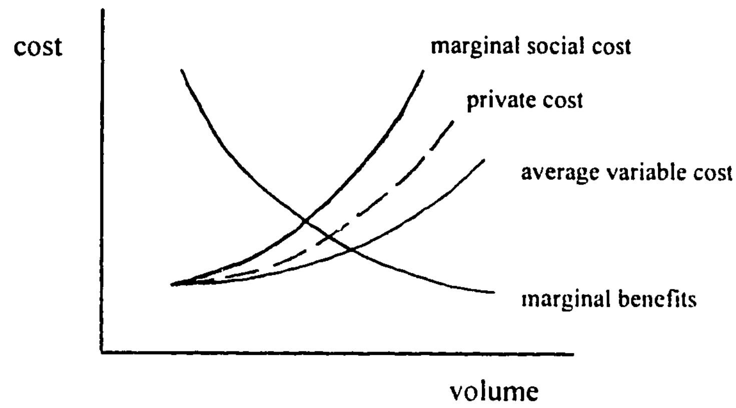

Figure 2-4. Illustration of User Charges (Source: Lewis, 1993)

The marginal social cost is plotted higher than the marginal private cost because delays to other drivers and environmental externalities are not considered by the road user. As the average variable cost increases (congestion increases), the gap between the marginal private cost and the marginal social cost increases. In effect, road users are not compensating other users and non-users for the external effects. A charge to road users that is proportional to the external effects of increased congestion, air pollution and noise would bring the two marginal cost curves closer together. The short term mobility decisions discussed earlier would be made in a new context. Eventually, the same could be said for the long term decisions.

2.2 Direct Demand Management and Road Pricing

2.2.1 Capacity Improvements Versus Demand Management

Difficulty has been encountered by metropolitan transportation authorities in abating noise and air pollution. Despite years of legislation to make air and noise pollution concerns a part of the transportation planning process, air pollution standards continue to be exceeded in urban areas. Likewise, congestion management has been made a part of transportation planning in many urban areas. The efforts to reduce congestion and vehicle noise and air pollution fall into four different categories: *infrastructure* capacity improvements, *traffic management* capacity improvements, indirect demand management, and an approach defined here as Direct Demand Management, where external costs are included in motorists' decisions.

Each of these categories of approaches to the problem of traffic externalities is discussed below. The four short term mobility decisions made by travellers provide a foundation for the ensuing discussion. The conclusions of this section are that if motorists have no direct financial incentive through Direct Demand Management to reduce their use of the road network and to stop emitting noise and pollutants, they will continue to make more trips, make longer trips and drive alone more. It is argued later in Section 2.2.5 that the most equitable and effective method of Direct Demand Management is road pricing.

2.2.2 Example of a Short-Term Decision: Choosing a Route

The hypothetical urban road network shown in Figure 2-5 has certain attributes. The lines with different thicknesses show roads with varying capacities. The network is typical of those in urban areas; the higher capacity freeway is fed by several arterials, which are in turn fed by collectors.

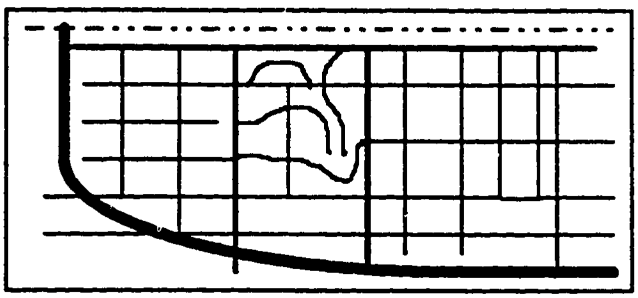

Figure 2-5. An Urban Road Network

A driver travelling through the community bounded by the freeway has a choice of routes to drive. The freeway has no signalized intersections, and has a higher posted speed limit than the other roads. The arterials, on the other hand, are interrupted by signalized intersections and are designed to accommodate lower speeds. The collectors may have even lower speed limits, respectful of design and safety constraints, and are likely interspersed with stop-controlled and signalized intersections. The collectors and arterials may be a more direct route for the driver.

The driver chooses a route using some combination of collectors, arterials and freeways. This is referred to as a *route choice* decision.

The driver takes into account several costs in making the route choice decision. In traditional traffic assignment modelling, the ratio of volume to capacity (V/C) governs the relative attractiveness of one route over another. These models assume that, given a choice of two different routes, a driver will choose the route with the lowest travel time. The travel time of the route is determined by the volume to capacity ratio of the roads; the higher the volume to capacity ratio, the more congested the road, and the greater the probability that the travel time of the route will be increased.

The three other steps in the travel demand modelling process, trip generation, trip distribution and mode split, also reflect short term mobility decisions on the part of individual travellers. The steps and the decisions they reflect are shown in Table 2-1 below.

Table 2-1. Steps in the Transportation Modelling Process

Step in the Model	Corresponding Short-term Mobility Decision
trip generation	- to make a trip and when to make it
trip distribution	- which destination to choose from a set of alternatives
mode split	- what mode of travel to use
traffic assignment	- what route to use

Drivers make these decisions without regard to many potential issues. Trip-makers might not make the same choices if these issues, or costs, were incorporated into their decisions. What if drivers were charged for the noise they create close to homes in the community? Depending on the cost, they might avoid routes in densely populated areas. What if single-occupant vehicles were charged for the marginal cost of the delay they create for other drivers by increasing the V/C ratio? The costs of delay, air pollution and noise are most obviously attributed to individual vehicles.

2.2.3 Volume, Capacity and Congestion

The fundamental basis for these decisions and the steps in the travel demand modelling process is the trip-maker's perception of the travel time between an origin and a destination, which is influenced by the ratio of volume to capacity. Volume can be defined as the number of vehicles passing a point on a roadway in a fixed time period. Volume is sometimes expressed as the number of people, rather than vehicles, that pass a point on a facility, but for the purposes of the discussion below the term represents volumes of vehicles. Capacity represents the maximum rate of flow of vehicles that the roadway can accommodate under given conditions. In crude terms, the volume to capacity ratio represents how "full" the roadway is. High volumes do not present a problem to motorists, in general, if the capacity is higher. Similarly, a roadway with a low capacity may be attractive to motorists if the volume is low. The term "congestion" refers to some point at which the volume to capacity ratio is high, depending on the expectations of the public and transportation authorities.

2.2.4 The Effects of Four Approaches to the Congestion Problem

As discussed above, congestion is accompanied by external costs, including delays to other road users, noise, and air pollution. The alleviation of congestion and related externalities in the U.S. is the task of transportation professionals and planners, as outlined in the CAAA and ISTEA. The four approaches usually used are discussed below. One approach to alleviating congestion is to build more infrastructure to accommodate the demand on the network. In other words, if the capacity of the road network is raised, the volume to capacity ratio can be reduced, effectively reducing congestion. However, in most urban areas, this improvement in the volume to capacity ratio permits more vehicles to use the network. The manner in which this occurs is described below.

Take a set of infrastructure additions: in congested areas, some lanes are added to existing roads in the network, and some new roads are constructed. The sequence of events following this improvement are shown in Figure 2-6. The initial volume in these congested areas is V1. The capacity of certain sections of the network is now higher, and has profound effects. First, STEP 1 - more trips may be made, or trips may be made in different ways, now that the cost of driving on the network, travel time in this case, is lower. Second, STEP 2 - the accessibility of destinations may change, making it easier for the traveller to make a longer trip. Third, STEP 3 - the attractiveness of using a single occupant vehicle is greater, resulting in changes in mode choice and increased vehicular volumes. Finally, STEP 4 - drivers perceive roads with lower volume to capacity ratios as being more attractive, and will shift their routes to include the new or improved facility in some cases. Thus, the volume to capacity ratio will increase despite the initial improvement. In this case, the externalities associated with congestion are multiplied by V2 vehicles; the external costs *per vehicle* return to the same level as before the improvement, and the *overall* external costs increase.

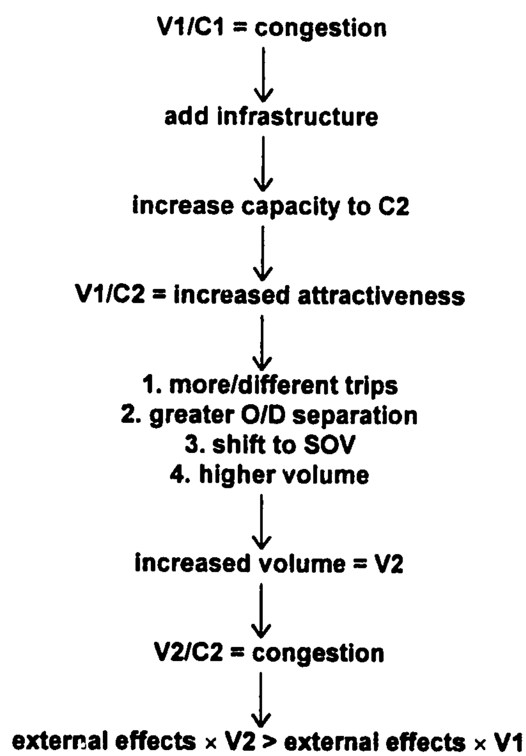

Figure 2-6. Possible Effects of Adding Infrastructure

In fact, if the goal of an urban area is to halt increases in overall external costs, congestion itself may be an ally. A congested network will eventually reduce the attractiveness of single occupant vehicle use, and may stabilize growth in vehicle traffic. Volumes, in other words, stop increasing because the capacity restricts growth. Although externalities remain the same on a per vehicle basis, the overall external costs stop rising. This is one of the driving forces, more so in Europe than in North America, behind the growth in traffic calming schemes (Tolley, 1989).

A distinctly different method of increasing the capacity of the road network has gained favor in recent years. This approach, categorized as traffic management capacity improvement, includes signal timing improvements and intelligent transportation systems (ITS) applications, many of which attempt to maximize the capacity of existing roadway infrastructure. ITS applications in this category include Advanced Traffic Management Systems (ATMS), Advanced Traveler Information Systems (ATIS), Automated Highway Systems (AHS), Commercial Vehicle Operations (CVO) and Emergency Vehicle Services (EVS). These approaches increase capacities by reducing headways between vehicles, reducing acceleration and deceleration delays due to intersection conflicts, incidents and toll facilities, and improving entrances and exits on freeways. They effectively increase the capacity of the road network, even though the infrastructure itself is fixed, by improving the conditions upon which capacity is dependent.

The results of this increase in capacity are identical in nature to those of an increase in infrastructure, as shown in Figure 2-7. The difference between this approach and the first approach is the cost of implementation. Adding infrastructure is costly in terms of materials, design and construction, traffic disruption, and public participation requirements. ITS improvements, however, are less disruptive and may have lower implementation costs, and are easily approved. Note that the benefits of such capacity improvements are substantial, and, especially in the case of ITS applications, have a high benefit to cost ratio. However, neither of these approaches are effective at reducing the external costs of noise and air pollution in the long term.

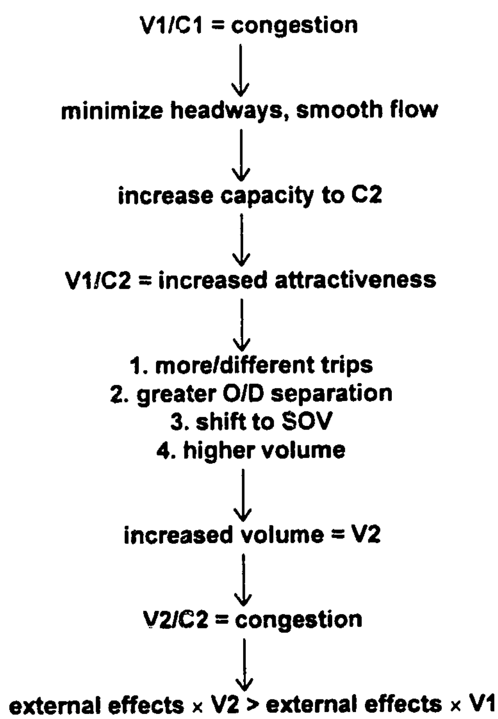

Figure 2-7. Possible Effects of Maximizing Capacity with System Management Improvements

Notice that both of these approaches attend to one half of the congestion problem: the capacity. The travellers' decisions are affected by the volume to capacity ratio; changes to either the volume or the capacity (or both) will affect travellers' decisions. If demand for the network exceeds capacity, the traffic volume will grow as long as there is available capacity. The network capacity, if so desired, can remain fixed. If traffic volumes are reduced and the network capacity remains the same, the volume to capacity ratio is reduced.

The third case is a special case, defined here as indirect demand management. Indirect travel demand management methods include giving network priority to transit vehicles, providing exclusive lanes for high-occupancy vehicles (HOV), improving bicycling facilities, and implementing ITS applications such as ATIS and Advanced Public Transportation Systems (APTS). The effects of improving HOV and transit travel times without attending to other network attributes are shown in Figure 2-8. Generally speaking, this approach involves improving the network travel times of vehicles with higher occupancies. This results in a shift in travellers from single occupancy vehicles, initially reducing vehicle travel while opening up capacity in the roadways of the network. Travellers' decisions are affected to the degree that the costs of travelling using the different modes has changed.

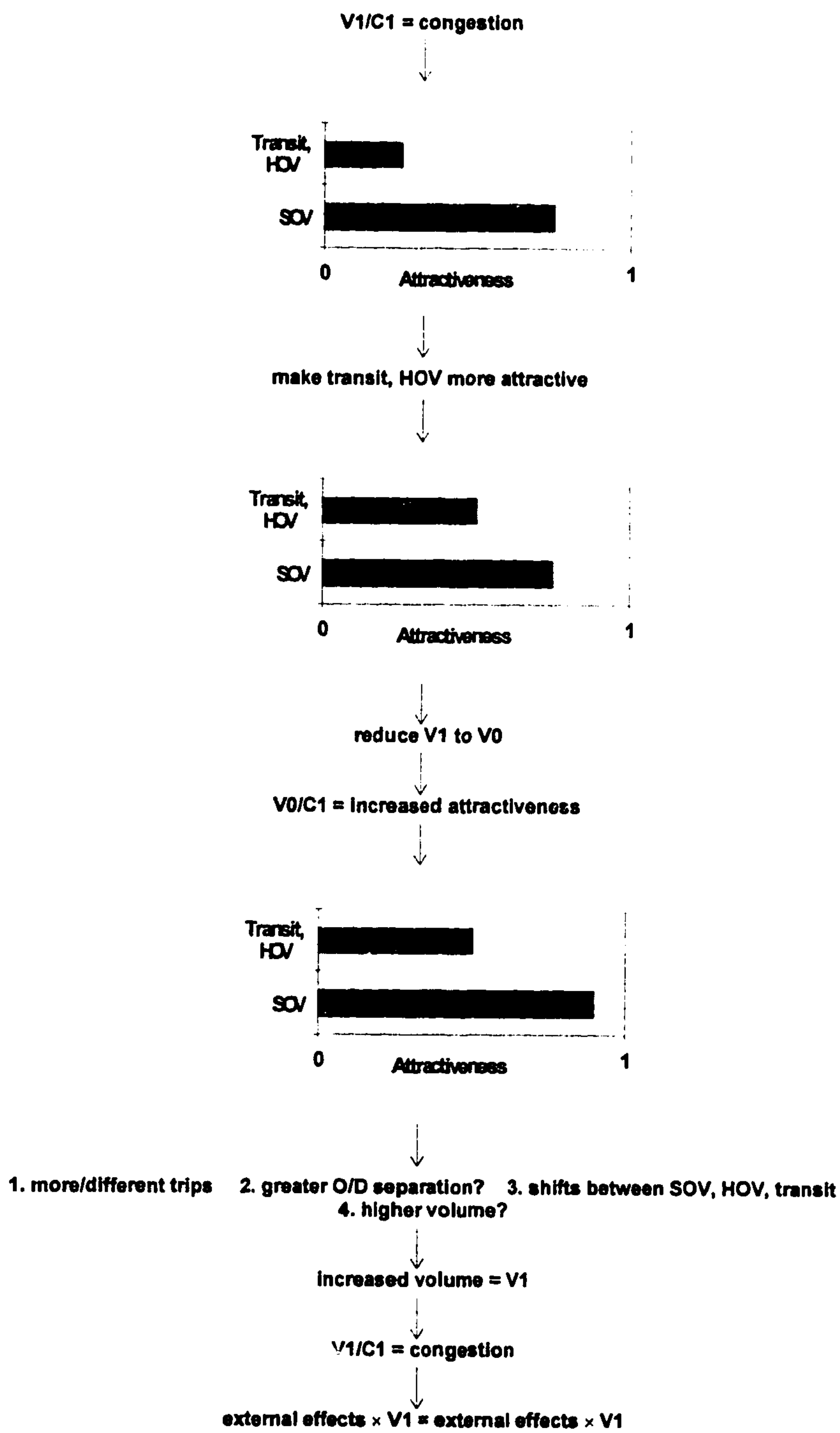

Figure 2-8. Possible Effects of Improving Transit, HOV Travel Times

The problem with this approach is that the single occupant vehicle demand is only slightly affected. The capacity of the road is increased. However, the third step, mode split, is affected slightly by the improved relative costs of the HOV and transit modes. The perceived cost of using a single occupant vehicle has also improved, thanks to the capacity improvement in the roadways. Transit priorities and HOV lanes alone may not change the perceived relative costs of single occupant vehicle use enough to significantly affect the decisions travelers make. There still exists potential for increases in vehicle travel, which result in less, the same, or perhaps greater overall external costs.

It is also important to note that HOV facilities may attract car pool travellers who previously used transit as their mode of travel. An improvement to the network of HOV lanes makes the use of transit somewhat more attractive, but also makes the use of automobiles with an occupancy of two or more people more attractive. The result could be an increase in the number of vehicle miles travelled and a decrease in transit ridership. Once again, these hypotheses are based on the assumption of the existence of latent demand for road use in urban areas.

Indirect demand management is partially effective because it attends to at least one of the components of people's travel decisions: the travel time on the road network. Direct Demand Management adds monetary out-of-pocket costs to the travel time costs that drivers perceive in choosing routes, choosing modes, choosing destinations, and choosing to make a trip. Approaches in the category of Direct

Demand Management include elevated parking fees, gas taxes, licenses to travel in specific areas, and road pricing. These approaches go further to close the gap between the marginal private cost and the marginal social cost of driving, as shown in Figure 2-4. The cost of single occupant vehicle use is directly perceived by drivers (in some cases more than others, as discussed later in this section). Direct Demand Management approaches can be structured to deal explicitly with the "volume" in the volume to capacity ratio, while leaving the "perceived volume to capacity ratio" the same or higher than it was before.

However, it is important to note that changing the cost of travel may not lead to an immediate reduction in trips or travel distances in an urban area. Increased travel costs would have a variety of short-term and long-term impacts. For example, consider the taxation of fuel, a widely applied economic instrument. Table 2-2 compares the total cost of gasoline and the tax on gasoline with gasoline consumption in eight developed countries. The data is plotted in Figure 1-9 below.

Table 2-2. Gasoline Use and Taxation in Eight Developed Countries (source: Flavin, 1996)

Country	Use (L/person)	Gas Tax ($/L)	Total Gas Price ($/L)
U.S.	1,600	0.09	0.34
Canada	1,124	0.21	0.46
Australia	936	0.24	0.53
Japan	364	0.3	0.65
Germany	497	0.48	0.66
Sweden	627	0.55	0.78
Italy	400	0.72	1
Portugal	235	0.85	1.21

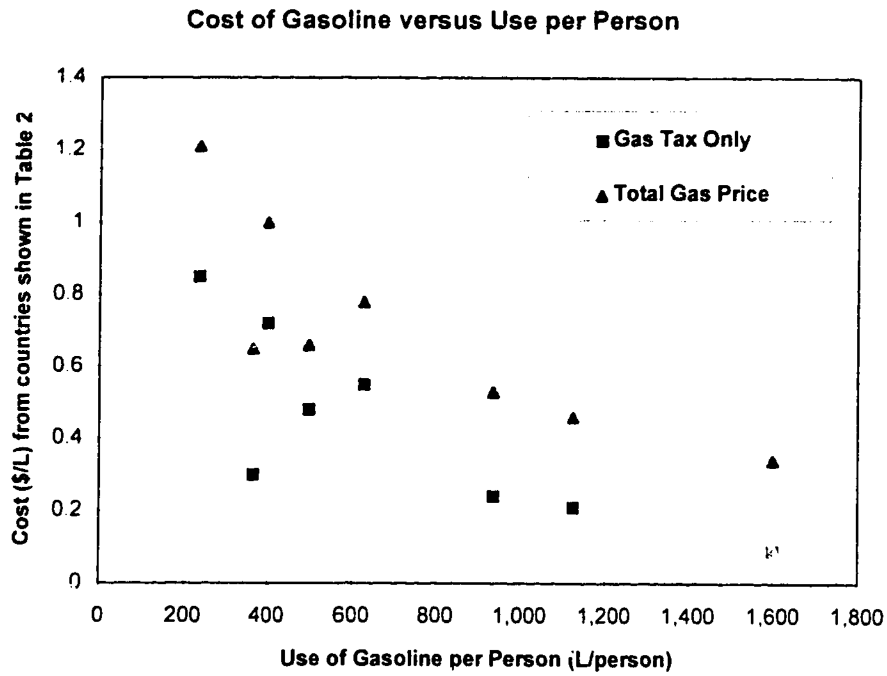

Figure 2-9. Cost of Gasoline Versus Use per Person (source: Flavin, 1996)

The graph indicates that gasoline use decreases as the gas tax increases. It is important to recognize, however, that each gas price/tax value is part of a different framework of household budgets and transportation choices in each country. There are many means by which consumers can lower their consumption of gasoline. Travellers may drive shorter distances in Europe than they do in North America. They may buy cars with smaller engine displacements in Canada compared to the United States, even though they travel the same distances. Similarly, it is difficult to predict the nature of the impacts of Direct Demand Management schemes designed to reduce air and noise pollution.

2.2.5 Direct Demand Management and Road Pricing

Equity is one of the greatest concerns to be addressed in the management of risks (Raynor and Cantor, 1987). From the perspective of implementing and estimating charges, equity concerns the distribution of costs and benefits among members of society (King et al., 1994). Equitable allocation of the costs of air pollution, noise, and congestion is required if Direct Demand Management approaches are to be accepted by the public. It is suggested here that road pricing is the most equitable form of Direct Demand Management.

2.2.6 Linking Road Pricing with the Generation of Air Pollution, Noise and Congestion

It is important to note that few of the Direct Demand Management techniques can be directly linked to air pollution, noise, and congestion. Gas taxes, for example, are rarely explicitly perceived by drivers, and are not linked to the driver's road use during peak hours, noise generation, or air pollution. Short term decisions such as a travellers' choice of mode and the structure of a trip are affected by the out of pocket costs incurred along the way. These out of pocket costs currently include such costs as gas prices, gas taxes and transit fares, as shown in Figure 2-10.

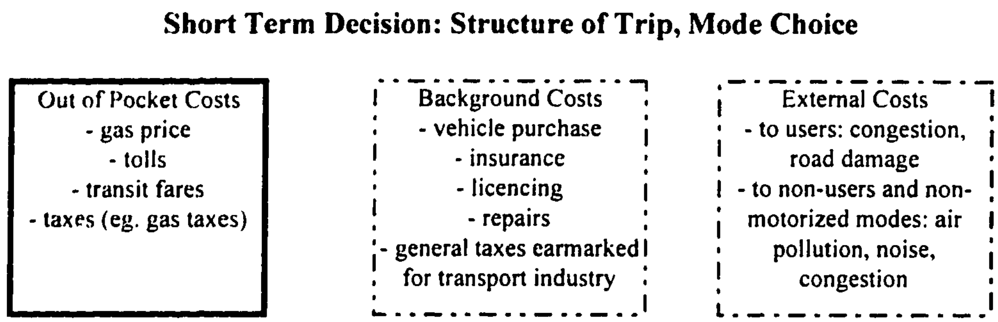

Figure 2-10. Monetary Costs Involved in Travel Decisions

In general, other costs, such as insurance costs, can be categorized as background costs - they do not affect the short-term decisions made by drivers. External costs are those costs not borne by the individual traveller. These costs, which include air and noise pollution and delays to other drivers, do not affect the short-term decisions travellers make. One of the goals of road pricing is to link the external costs and existing taxes to driver behavior, such that these short-term decisions are made by drivers in the new context described in Section 2.1.

Another purpose of road pricing is to distribute the costs of sustaining transportation facilities more equitably. Figure 2-11 illustrates the costs borne by road users, transportation agencies, and non-users.

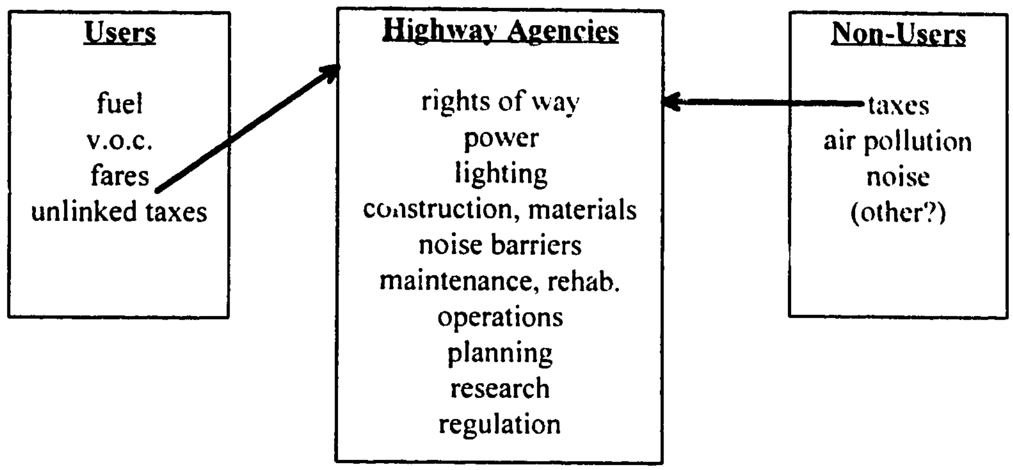

Figure 2-11. The Bearers of Highway Costs

Non-users bear the costs of air pollution and noise pollution almost exclusively. Taxes, which are collected from different sources including gas taxes (buried in the price of gasoline) and general tax revenues, are used by highway agencies to plan, operate and maintain the road network. For the reasons discussed in Section 2.1 it is desirable to shift the burden of highway agency costs and external costs onto road users. This scenario is shown in Figure 2-12.

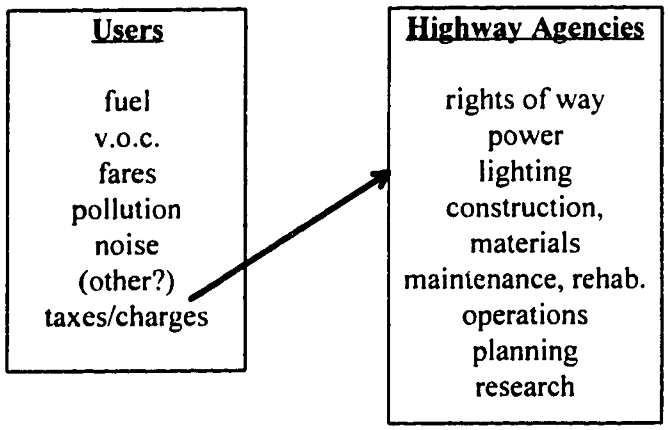

Figure 2-12. Road Pricing Arrangement and Highway Costs

Charges could be collected from vehicle operators on an average cost basis, where responsibility for the costs shown in the first box in Figure 2-12 is attributed to all road users. Funding transportation facilities through road pricing based on average cost pricing would be an improvement over the present system of gas taxes and transportation appropriations. However, to truly be based on sound microeconomic theory and to attend to equity issues, road user charges would be based on marginal cost pricing principles. If planned intelligently, however, charges based on average cost principles as discussed in this thesis will link travellers' decisions with the external costs they occasion, while conforming to an equitable allocation structure.

2.3 Concluding Remarks

The impetus for a change in the way the road network market operates is based on the concept of the tragedy of the commons. Presently, the road network operates as a common facility. Using the road network does not impose costs on anyone in the eyes of drivers. Travellers will continue to add single occupant vehicles to the road network until they can no longer stand the congestion. As this point, the marginal benefits they incur are outweighed by the costs of congestion they perceive. No matter how much a single driver increases everyone else's travel time, if the benefits outweigh the costs to the individual, he or she will continue to use the road.

The trouble is, in the meantime, the general public is being subject to uninvited risks due to air pollution and noise, and the long term activity choices that are influenced by travel decisions are leading society in somewhat unwelcome directions. This chapter has presented the argument that road pricing is an attractive method of making drivers aware of the costs of air pollution and noise that are borne by residents in urban areas.

If trip-making decisions are to be influenced by road user charges, a host of questions arise. What if vehicle operators were only assessed charges in one section of the road network? Should vehicles be charged differently if their pollutant emission characteristics are different? What if drivers' behavior varies significantly: would the cost of noise or emissions borne by aggressive drivers be higher than that of others? Finally, if travellers were to incur the costs of air pollution and noise that they occasion, how would these costs be equitably allocated?

Chapter 3

Literature Review

3.0 Introduction

This chapter establishes a fundamental basis for the analysis performed in Chapters 4 and 5. A literature review is presented in five sections: 1. Road Pricing, 2. Equity in Road Pricing and Cost Allocation, 3. Motor Vehicle Noise Pollution, 4. Air Pollution, and 5. Monetary Valuation of Pollution. For clarity, a glossary of terms is included as Appendix A.

3.1 Road Pricing

The focus of this section is the concept of charging road users directly to recover the costs associated with transportation. The impetus for charging road users introduced in Chapter 2 is refined with additional ideas from the literature. The application of a particular form of road pricing, congestion pricing, and relevant issues are presented. The possibility of implementing a road pricing scheme that includes charges for air and noise pollution is discussed.

3.1.1 Markets and Externalities

According to basic microeconomic theory, markets for goods are determined by supply and demand. The supply of a good is the amount of the good provided by manufacturers. The demand is the amount of the good desired by consumers. As demand increases, the price of the good increases. When demand decreases, the price of the good decreases. In markets, prices interact with supply and demand while moving towards a point of equilibrium where supply and demand are equal. Markets are said to work efficiently when people maximize their self interest by doing what is economically advantageous for them. There are some restrictions to this statement, however (Anderson et al., 1977). Individual units of consumption must be small relative to the size of the market. Producers and consumers must be fully informed about present and future prices. Individuals must not affect the costs or satisfaction of those around them. Finally, buyers and sellers must be able to exit and enter the market freely.

In the case of road use, the individual units of consumption, trips, are very small compared to the size of the market, the total trips in an urban area. Individuals can exit and enter the market for road use reasonably freely; they only have to qualify for a driver's license and be able to insure a vehicle. However, the other two requirements of an efficient market for road use are contentious ideas. Firstly, it can be argued that producers and consumers of highway travel do not fully grasp present and future prices. It is widely cited that the perceived costs of driving are much lower than the actual costs of driving (Lee, 1995). Secondly, it is now recognized that road users affect the costs and satisfaction of those around them. For example, the travel time of all system users (consumers of highway travel) is increased by the addition of a vehicle to traffic. Money from non-users is often used to construct noise barriers. Air and noise pollution adversely affects people living or working next to congested roadways. For the market for highway travel to be more efficient in the traditional microeconomic sense, the actual costs of driving must be perceived by drivers and the adverse impacts on other consumers must be reduced or compensated.

Externalities are the effects of consumers' actions which impact the satisfaction of others without compensation (Anderson et al., 1977). The external benefits of a good, such as the enhancing beauty of a farm building as seen by travelers, are not factored into the decision to buy the good or the decision to sell it. Likewise, the external costs of a good, such as the noise produced by a bus, are not factored into the decisions to buy or sell the good. These externalities lack markets altogether. People value them to varying degrees, just like other goods, but the fact that property rights cannot be assigned to individuals in the literal sense makes it impossible to exchange many externalities on the market (Freeman 1979). The price of clean air, for instance, is not known, because no one possesses any. The effect of external costs is that people are enjoying benefits at the expense of the environment and others' satisfaction (Button, 1994). As mentioned before, the transportation market does not function efficiently when the consumption of travel creates externalities.

Externalities in transportation can be local effects, transboundary effects, or global effects (Button, 1994). An example of a local effect is the noise produced by a passing truck. The effects of noise are concentrated in a relatively small area around the moving truck. Transboundary effects might be produced in one area, but can affect people or the environment in other areas (Button, 1994). An example of a transboundary effect would be acid rainfall in one city that is produced in part by the sulfur dioxide emissions from factories and vehicles in another country. Finally, global effects are felt world-wide and may be produced world-wide. Climate changes resulting in part from massive carbon dioxide emissions are examples of global effects. The distinction between these three categories of effects is needed to determine who is affected and who is responsible for the impacts of pollution.

Costs that are external to the decision to drive to work include those that affect other drivers and those that affect non-drivers and the environment (Button, 1994). Congestion is an externality that affects other drivers. The presence of one more vehicle on the road during rush hour increases the travel time and frustration for other road users. Externalities affecting non-drivers include noise and air pollution. None of these externalities are included in the driver's decision to make a trip (Lewis, 1993). As a result, the marginal private cost to the driver is lower than the marginal social cost to all groups, including other drivers, residents, and the environment (Lewis, 1993). The goal of charging for noise and air pollution is to make the user pay for the difference between these costs and make these externalities internal to the decision to drive.

Some economists argue that the pricing of pollution should be based on the idea that clean air and quiet surroundings are scarce resources, and that pollution is a use of these resources that should be priced just as other scarce resources are priced. The more pollution is reduced, the more it will cost society to reduce it by a further unit (Beckerman, 1990). There is, therefore, an optimum point where the costs of reducing pollution by one more unit are equal to the costs required to achieve this i... ction. Pollution generators would ideally, from an economics perspective, be charged in the same for their use of clean air and quiet as they would for other scarce resources, such as motor oil or platinum.

For a true market to be created for these scarce resources, a system of property rights would have to be set up upon which trading could take place. For instance, if property rights to quiet could be sold to residents in a community, the residents could sell the right to pollute to motorists (Button, 1994). The price of the right to pollute for each parcel of "quiet" would be determined by how much the residents valued quiet, or their willingness to pay for quiet (Walters, 1975). The concept of charges requires the simulation of this hypothetical market. It is generally accepted that conferring property rights to clean air and quiet is very difficult (Freeman, 1979). The best that can be done is to approximate the value that residents put on clean air or quiet, and charge road users on the basis of that value. The valuation of clean air and quiet is discussed in Section 3.5 of this chapter.

3.1.2 Existing Arrangement of Transportation Taxes and Revenues

The present arrangement of charges that drivers pay could be described as indirect charges. In Canada at present, there are taxes paid to the government by road users in the form of gasoline and diesel fuel taxes, licensing and registration fees for drivers and for truck operators, and provincial and federal sales taxes. Users thus pay both vehicle ownership taxes, such as license fees, registration fees and sales taxes, and variable user charges, such as sales taxes on tires and gasoline and diesel fuel taxes (Lewis, 1993). These are not effective methods of collecting tax revenues for two major reasons. First, in Canada these taxes are not directly earmarked for transportation maintenance and improvements, and revenues are not always spent in the jurisdiction in which they were collected. Second, these taxes do not have any direct connection with the choices drivers make, and are not equitable charges for the social costs of driving. In the US, gasoline taxes are earmarked for the transportation sector through trust funds, but are still buried in the cost of the gasoline. Drivers cannot associate these taxes with peak-hour road use, pollution of residential air, or use of urban space in parking.

A tax attached to the purchase price of a vehicle would not be as effective at pricing the marginal costs of driving a vehicle. A gas tax comes closer to pricing the marginal costs of venicle trips because a driver can associate it with the use of the vehicle (Banister, 1994). The effectiveness of a gas tax in influencing driver choices depends on whether the use of the motor vehicle is essential or voluntary. However, the road user charge should be based on the difference between the marginal cost and the average variable cost of the trip, as discussed in Chapter 2 (Lewis, 1993). This can be accomplished by applying direct charges that account for the levels of costs under various scenarios (facility type, section of the road, population living nearby, time of day, traffic volume).

3.1.3 Examples of ITS Road Pricing Technology

The technology used to electronically collect charges can be categorized as in-vehicle or off-vehicle technology. In-vehicle technology includes smart cards (data cards with computer chips inside), odometers (distance measuring instruments), time monitors, and transponders (tags that transmit signals but do not store information) (Lewis, 1993). Off-vehicle technology includes toll booths and electronic toll equipment. Using different arrangements of these technologies, tolls can be collected based on a drivers' point of progress, travel time, or distance travelled. The essential components of electronic tolls, the technology upon which noise and air pollution charges are dependent, are in-vehicle communications, roadside two-way communications, vehicle detectors, and a communications network. There are many options available for the communication of information between the roadside and the vehicle. The vehicle might have a read-only tag, from which data about the vehicle can be obtained. The vehicle might have a read-write log, which can record information sent from [illegible] roadside communicator. The vehicle might be equipped with a transponder a[illegible] a m[illegible]cro-processor or user-held smart card. There are advantages to each of these technologies. Read-only tags require vehicle travel information to be recorded by the road operator, a concept which gains limited acceptance from the public. A read-write log is simpler technology, but a log of drivers' activities is required. Smart card technology is more expensive, but is very flexible and can be applied in conjunction with other purposes, such as banking, credit accounts, and licensing. Electronic toll collection technology has improved rapidly since the mid-1980's; the use of electronic toll collection equipment for road pricing is now possible (Ahrenholtz, 1995).

Different forms of congestion pricing are being implemented around the world. One might find that a natural extension of congestion charges in these examples will be charges for noise and air pollution. Variations on the theme of road pricing have been implemented in Oslo, Bergen and Trondheim in Norway, in Stockholm and Gothenberg in Sweden, and in Singapore (Lewis, 1993). Ten miles of State Route 91 in California have been opened to vehicles equipped with electronic toll tags; the toll on the facility increases as traffic congestion on other routes increases (Ahrenholtz, 1995). Such schemes have received varying degrees of public acceptance, a subject discussed in the next two sections.

3.1.4 Institutional Requirements

The public may perceive road user charges simply as another form of government revenue generation (Banister, 1990). This is convincing reason to make explicit the distribution of revenues from charges. The revenues should not be pooled in general government funds, let alone in a general transportation fund. Revenues from the charging scheme may have to be distributed completely differently from existing tax revenue arrangements (Banister, 1990). Congestion, air pollution, traffic noise, and pavement quality are all seen as pressing problems, but a jurisdiction would be lucky to get a majority of public approval for a charge for road use (Lewis, 1993). There are, of course, many more institutional requirements to maintain support for the pricing scheme and the chosen allocation design. Above all, there must be a measure of benefits to indicate that the scheme is achieving its goals.

3.1.5 An Analogy

To visualize the role that road pricing might play in tl. of transportation funding, consider that the role of the transportation agency is essentially to regulate the highway network market. It is comparatively easy to describe the markets for other goods:

perfect competition - many producers making a variety of goods; markets for clothing, handicrafts are close to perfect competition.

monopoly - market dominated by a single seller; the operation of a utility such as gas or electricity is an example of a monopoly.

oligopoly - market consisting of two or more sellers, at least one of which makes up a large fraction of total sales; an example of an oligopoly would be the market for cement.

The highway network can best be described as a regulated oligopoly, with services offered by different levels of transportation agencies: the Federal Government, State/Provincial Transportation Departments, and local metropolitan planning organizations. In a monopoly and, to a great extent, in an oligopoly, one firm has the power to set the prices for its product (Galbraith, 1973). In the case of a private firm attempting to maximize its profits, the firm sets the price at a level that will maximize financial returns. A monopolist can determine a product's price directly by varying its output (Vogt, Cameron, Dolan, 1993). In the case of a highway network, a controlling agency could set the price of driving at an equitable level. In this manner, the highway network market structure would resemble that of a phone company, which can be described as a monopoly at the local level. Rates are set by the phone company to recover costs as well as to influence demand on the network; higher long distance rates are established for high demand periods. In a similar fashion, rates for road use could be set to influence demand on the road network. An important distinction, however, is that congestion in phone lines only imposes costs on fellow phone users, whereas congestion on roadways imposes costs on non-users as well (Sullivan, 1996). The analogy cannot be taken too literally, but does serve to illustrate the concept of road pricing.

3.2 Equity in Road Pricing and Cost Allocation

This section is split into two parts. The first discusses equity as it pertains to the introduction of user charges. The second investigates the notion of equitably allocating external costs.

3.2.1 Equity in Establishing a System of Charges

A policy is more likely to be deemed acceptable by the public if it is instituted with attention to equity (Raynor and Cantor, 1987). Equity is a concept with many different forms and interpretations, all of which should be considered in planning a road pricing scheme. The interpretation of these concepts is bound to differ as much as social ideologies differ from person to person. Several equity concerns that are addressed by the analysis in Chapters 4 and 5 are outlined below.

Formal equity is the equal treatment of people within a reference group (Hay and Trinder, 1994). Today, for example, many non-users pay the costs of road users' noise pollution. If non-users were compensated with a flat rate toll from road users, then operators of quiet vehicles would be providing just as much compensation as operators of louder vehicles. Charging users for noise in direct proportion to the noise their vehicles generate would adhere to the concept of formal equity.

The concept of distributional equity is an important consideration in road pricing. Distributional equity is concerned with the effect of policies on the distribution of income in society (Rosenbloom and Altshuler, 1977). The degree to which lower income groups receive the detrimental affects of policies should be examined. Distributional equity would be important in determining what is done with the revenue generated from noise or air pollution charges. Experience with congestion pricing outside North America has shown that there is less public objection to pricing plans when revenues are invested in public transit and pedestrian improvements (Lewis, 1993). If the revenues from noise charges, for example, were used to compensate those groups who can least afford the charges, the plan would adhere to distributional equity. Distributional equity is also referred to as vertical equity, in that all levels of income are afforded equal opportunities in society (Banister, 1994).

Procedural fairness is an equity concept which entails consistency in the development of a policy (Hay and Trinder, 1994). No one group, be it a community bicycle awareness group or an auto club, should be permitted to completely dominate the construction of a road pricing scheme. On the other hand, liberty rights must be observed; affected groups must all be able to ha[illegible] in the enactment and operation of the program.

Equity in expectations refers to maintaining conditions upon which expectations have been formed (Hay and Trinder, 1994). The pricing of roads for air pollution should be done in a gradual fashion that allows manufacturers to supply cleaner vehicles, or allows public authorities time to accommodate mode split transitions. The ease of this transition will depend on how quickly costs can be shifted around within the urban transportation and trucking industries (King et al., 1994).

Note that in this discussion transportation is forwarded as a "right", rather than simply a marketable "good". Accessibility can be described as a right; each member of society deserves the right to engage in activities outside the home. Mobility, on the other hand, might be described as a good; the ability to live as far from one's place of work as one's affordable mobility permits is not a necessity. That mobility can be thought of as a marketable good. The ability to get from home to work, however, is a necessity. The accessibility of the workplace, then, can be thought of as a right.

Some equity considerations are specific to the price that is chosen. Formal equity must be observed when setting overall air quality emissions targets that are more difficult to attain in one area than in another, say, because of the nature of industry in the areas. Or, to give another example, if the damages due to noise pollution are not as great in a commercial district as in a purely residential district, a uniform noise charge in the city would be inequitable (King et al., 1994). If charges produce a distribution that is unfavorable, the distribution of revenue can be used to make the outcome more equitable. It is argued by many that lower income groups are impacted the most by pricing schemes (Banister, 1990). Note that households faced with a new automotive expenses must allocate money from other areas of their lives, such as food or entertainment, to transportation if they are to continue making the same number of trips using the same mode (Banister, 1990). These household budget changes impact lower income groups more than higher income groups. Lower income groups tend to make less trips, own fewer vehicles, and can least afford to pay for the noise and pollution they create. This inequitable distribution can be aggravated if public transit service is poor. This is a significant obstacle facing a charging scheme.

However, the money raised in the form of charges can be used directly to redistribute wealth among income groups. For instance, if it is recognized that poor transit service and high charges for road use leave lower income groups with relatively expensive alternatives, the revenues from the charging scheme might be used to improve transit service to the benefit of these groups. In another example, if it is found that the increase in vehicle miles traveled is being curbed but that older vehicles with poor pollution control are being kept on the road longer, then it would be desirable to use the money raised in the pricing scheme to buy out older and poorly maintained cars. Society might be willing to pay to reimburse the drivers that cannot afford repairs or newer vehicles under the road pricing regime.

3.2.2 Equity in Cost Allocation

As mentioned in the previous section, there are different concepts under the label of equity. Any system of charges can be described as being equitable. It is the definition of equity and the form of equity on which the system is built that is of concern. A discussion of equitable cost allocation should centre on the responsibility of road users for overall costs.

It can be said that there are three requirements of a system of highway cost allocation: 1. Completeness, 2. Rationality, and 3. Marginality (Villarreal-Cavazos 1985). Completeness entails that the costs of building and operating a road must be totally financed by the users of the road. This is often a point of contention in policy making, as it is often argued that there are reasons to appropriate some costs to the general public to subsidize the use of roads by national defense vehicles and farm vehicles, for example. The requirement of completeness has been accepted in the case of highway construction and maintenance cost allocation. It has been argued in

Chapter 2 that this should be extended to be a requirement of air and noise pollution cost allocation.

The second requirement, that of rationality, simply states that the allocation of costs of a road used by different vehicle classes should not make an exclusive facility more economically attractive (Villarreal-Cavazos, 1985). In other words, the same method of cost allocation should be used on all facilities in the road network. This requirement underscores the need for a road pricing scheme that is applied to all roadways with the same rationale.

Given that the users of the road are financing the total costs (the Completeness requirement), Marginality requires that the costs allocated to a vehicle class are sufficiently high to cover the marginal costs occasioned by the class (Villarreal-Cavazos, 1985). To fulfill this requirement, the charges assessed to a vehicle must be equal to the costs for which it is responsible. An appropriate measure that satisfies this requirement is the determination of the user's share based on causal relationships (FHWA, 1984).

These three requirements are independent of each other, and should all be accounted for in the cost allocation procedure. By developing a method of allocating the full costs of air and noise pollution based on the actual responsibility of individual road users, and by implementing this procedure on all sections of the road network, these requirements can be met.

It is useful to consider the traditional allocation of pavement costs at this point. The two methods traditionally used are the incremental approach and the occasioned cost method. The incremental method has been widely used in the past (FHWA, 1984). It involves allocating highway costs to vehicle classes based on the construction or rehabilitation required to accommodate each successive vehicle class, beginning with the required thickness of the lightest vehicles. This method has been shown to be inconsistent when the order of successive application of vehicle classes is changed (Villarreal-Cavazos, 1985). Past experience has shown that unjustifiably large responsibilities have been assigned to lighter vehicles in pavement damage cost allocation (FHWA, 1984). The occasioned cost approach is a more rational cost allocation method. Users are charged in proportion to the pavement damage that they cause, or, in other words, the costs that they occasion (Wong and Markow, 1982). Of these two methods, only the occasioned cost approach can be considered equitable

In all, Wong and Markow describe three forms of equity relating to cost allocation: 1. Received Benefit Equity, where the assignment of costs parallels the benefits that each person receives from the policy; 2. Ability to Pay Equity, where the assignment of costs is a function of each person's ability to pay; 3. Occasioned Cost Equity, where costs are assigned in proportion to the costs induced or occasioned by each person. In transportation cost allocation applications, Received Benefit Equity and Ability to Pay Equity have generally been shunned. Occasioned Cost Equity has been advocated for use in highway cost allocation (Rilett, Hutchinson and Haas, 1988).

Three different types of costs are allocated with regards to highways: 1. Uniquely Occasioned Costs, 2. Jointly occasioned costs, and 3. Common costs (Wong and Markow, 1982). Uniquely occasioned costs are those that can be attributed to one vehicle class alone. An example would be the cost of constructing hill-climbing lanes for heavy trucks (Wong and Markow, 1982). Jointly occasioned costs are costs that can be attributed to more than one vehicle class to varying degrees. An example of jointly occasioned costs are the costs of pavement deterioration, for which all vehicles are responsible, but for which trucks are far more responsible that automobiles (Rilett, Hutchinson and Haas, 1988). Common costs are those costs for which there is no discernible difference in the responsibility of one vehicle class and that of another. A common cost related to highways is the cost of acquiring a right-of-way (Wong and Markow, 1982). It will be shown in Chapters 4 and 5 that different vehicle classes are responsible for noise and air pollution to varying degrees. Thus, the costs of air and noise pollution due to road traffic can be considered joint costs. The allocation of joint costs using the occasioned cost approach satisfies the requirements of an allocation scheme mentioned earlier. The method only allocates costs to road users, satisfying the Completeness requirement. The vehicle classes are allocated costs directly proportional to the costs for which they are responsible, which satisfies the Rationality and Marginality requirements. To allocate responsibility for these costs using occasioned cost equity, a responsibility measure must be identified using characteristics that are common to all of the polluting vehicle classes. This area will be examined in Chapters 4 and 5.

3.3 Motor Vehicle Noise Pollution

Reducing traffic noise pollution has become an important goal of metropolitan transportation authorities throughout the world. Traffic noise is the single greatest contributor to urban noise pollution and is responsible for annoyance and health problems related to stress. As a result, ways to reduce noise due to traffic congestion are continually sought by urban planners and transportation engineers. The accurate prediction of traffic noise is needed for the determination of noise levels associated with different transportation project alternatives, verification that transportation projects will meet applicable noise standards, the evaluation of noise abatement strategies (Hajek and Krawczyniuk 1983), guidance for the location of residential development (Cannelli et al. 1983), and for input to environmental impact studies.

As an introduction to the empirical approach to modelling traffic noise, ten demonstrated and popular noise prediction models used across North America and Europe are presented. In this section, fundamental principles of traffic noise and its prediction are discussed. In Chapter 4 ten prediction models from North America and Europe are introduced. Both low-speed interrupted flow models and high-speed uninterrupted flow models are examined, and functional forms common to all the models are investigated. Variables describing traffic noise generation and propagation are also investigated in Chapter 4.

The problem of vehicle and traffic noise associated with traffic networks has been gradually gaining public attention over the past forty 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 (Alexandre et al., 1975).

3.3.1 Sound and Noise Principles

While noise may be described physically in the same manner as a disturbance (vibration or pressure change) in an elastic medium, it is usually defined in transportation engineering applications in a subjective manner (Harmelink, 1970). Sound is a form of energy and it has a pressure associated with it. The human ear is capable of discerning a sound (i.e., a powerful engine) that is a million times higher than the faintest possible sound that may be detected. The historic means of dealing with this range in magnitude has been to adopt the relative scale "level" concept from acoustics. A level of a quantity is defined as the logarithm of that quantity to a reference quantity of the same kind. One common means of quantifying sound energy is the sound pressure squared. The sound pressure level (SPL) of a sound pressure p is defined in decibels and is shown in Equation 3-1.

[3-1] $$SPL = 10\log_{10}\frac{p^2}{p_{ref}^2}$$

where

p_{ref} sound pressure of the weakest sound that may be heard in an extremely quiet location.

The value of p_{ref} is usually taken to be 20 uPa (.002 microbars) and the constant (10) is used only for convenience (10 bels = 1 decibel). The more familiar form of Equation 3-1 is shown in Equation 3-2 below.

[3-2] $$SPL = 20\log_{20}\frac{p}{20}$$

When two or more separate noise sources are combined, the resultant SPL of the combination is not a direct summation of the two SPL values but is rather a function of the resulting pressure. This resulting pressure may be calculated using Equation 3-3.

[3-3] $$p_{res} = (p_1^2 + p_2^2)^{0.5}$$

The end result of Equation 3-3 is that the SPL value resulting from the combination of the two noise sources is never more than 3 dB higher than the larger of the two.

3.3.2 Traffic Noise

There are two types of noise sources that are of interest to transportation engineers. The first is the point source such as that produced by a vehicle traveling down a roadway with no other traffic around. The sound pressure for this type of source varies inversely with distance such that for each doubling of distance the sound pressure is halved. This relates to a reduction or increase in SPL of 6 dB depending on whether the distance is doubled or halved respectively. The second type is the line source such as that produced by a continuous stream of traffic. In this situation the sound pressure waves are cylindrical and the associated sound pressure varies inversely as the square root of the distance. Therefore, for a doubling of distance the sound pressure is reduced from p to $p^{1/2}$. The actual reduction or increase in SPL is therefore dependent on the original sound pressure.

Although sound pressure and the SPL value may be easily measured and calculated the effect on the auditory systems of human beings are a little more complex. Sound may be ordered on a scale from soft to loud and from this the "loudness" of a sound may be derived. The unit of loudness measurement is the sone and one sone corresponds to a pure tone of frequency 1000 Hz that is 40 dB above the sound threshold. Any other sound is a fraction or multiple of this base situation. A more common unit is the loudness level measured in phons which is numerically equal to the sound pressure level in decibels. Loudness depends not only on the sound pressure level but also upon the frequency and wave form of the stimulus.

Sound meters used in traffic noise measurement obviously pick up 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 SPL values into measurements of the subjective sound level. The sound level is also 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 (Favre, 1978).

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 level from observational data is shown in Equation 3-4.

[3-4] $$L_{eq} = 10\log_{10}[\frac{1}{100}\sum_{i=1}^{n} f_i 10^{l_i/10}]$$

where

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

It may be seen that any number of vehicle classes , any division of time, and any weighting of the noise from different classes can be applied using the formula.

3.3.3 Traffic Noise Prediction Methods

There are a variety of traffic noise prediction models that are used worldwide for assessing the potential noise levels for new roadways or noise levels in the future due to traffic increases. There are essentially three different ways to approach the prediction of traffic noise. One method is to build scale models to recreate the area of interest and measure the noise produced by miniature sources (Favre, 1987). Alternatively, theoretical models may be derived which predict noise levels based on such variables as sound intensity and distances from sources (Takagi et al., 1974). The most widely used method of traffic noise prediction is the use of empirical models that are based on measurements of noise in the field. The discussion of models in Chapter 4 represents a comprehensive overview of empirical models in use in North America and Europe. All the models that are examined attempt to relate the overall noise level emanating from one or more road segments based on their respective physical attributes and traffic characteristics. The unit of noise in the models is the decibel (dB) and the dependent variable in the models is either the sound level L_{10} or the equivalent continuous sound level, L_{eq}. The noise from the road segment is assumed to be generated from a line source.

All of the noise prediction models have a general linear additive form as shown in Equation 3-5. In the models examined there were 12 variables identified as affecting traffic noise and these variables can have a linear or logarithmic affect on the sound level. An overview of the different models and the relevant variables is presented in the following sections.

[3-5]

$$L_x = A + \sum_{i=1}^{n} B_i \log_{10} X_i + \sum_{j=n+1}^{m} B_j X_j + \sum_{i=1}^{n} \sum_{j=n+1}^{m} B_{ij} f(X_i, X_j)$$

where	x	sound level descriptor: eq, 10, 50, or 90
	A, B_i, B_j, B_{ij}	constants derived from field samples
	X_i, X_j	variables that influence noise level at receiver.
and	$f(X_i, X_j)$	an interaction term used only in Model 1 and discussed in Chapter 4.

The models have similar mathematical approaches to estimating noise levels. There are two different prediction regions, one characterized by interrupted flow and speeds below 50-60 km/h and the other by free flow and speeds above 50-60 km/h. All of the models take into account the influence of traffic volume and composition on generated noise levels. Those models specifically designed for the interrupted flow regime do not include speed as a factor influencing noise generation, but those designed for the free flow regime do. The models use different breakdowns of traffic composition, and that their equations reflect differences in the contributions of specific vehicle types to noise levels. The ten models vary in their treatment of the propagation of noise in the prediction of noise levels.

As mentioned in Chapter 1, a critical component to any equitable road pricing strategies is that a suitable responsibility measure needs to be identified. The final section of Chapter 4 explores the potential use of the models to establish responsibility measures for noise for use in cost allocation.

3.4 Motor Vehicle Air Pollution

The following section is a discussion of motor vehicle emissions and pollution. The major pollutants of concern are defined, and their harmful effects are discussed. It is then shown that motor vehicles' contribution to pollution is significant enough, particularly in urban areas, to warrant attention. Future trends in emission levels and major regulatory actions in North America are discussed in brief. Finally, the methods of predicting emissions are introduced. Later in Chapter 5, the factors influencing vehicle emissions are discussed as a foundation for the derivation of measures of responsibility for different vehicles.

3.4.1 Pollutants of Concern

There are many different substances that are categorized as vehicle pollutants or emissions. These can be separated into two groups: primary emissions that are emitted directly from the vehicle and secondary emissions that are produced by transformations or reactions between primary emissions and other precursors (Lenz, 1994). The primary pollutants of major concern are carbon monoxide, hydrocarbons, nitrogen oxides, lead, sulfur dioxide, and particulate matter. Carbon monoxide (CO) and hydrocarbons (HC) are produced by the incomplete combustion of fuel (OECD Transport and the Environment, 1988). Hydrocarbons often include volatile organic compounds (VOC's) when discussed in the context of urban air quality (Horowitz, 1982). The combustion of fuel at very high temperatures results in the formation of nitrogen oxides (NO_x) (OECD Transport and the Environment, 1988). Lead (Pb) is emitted from the burning of leaded gasoline, which has been banned in North America. Suspended particulates are emitted from all vehicles. Disproportionate amounts of toxic particulates are emitted from diesel engines. These particles are very small and remain airborne for long periods of time (OECD Transport and the Environment, 1988). Combustion of diesel fuels also results in the emission of substantial amounts of sulfur. Carbon dioxide (CO_2) is emitted by all vehicles and is of concern because of its contribution to the greenhouse effect.

Other harmful gases are formed from these vehicle emissions and are known as secondary emissions. Photochemical oxidants, the most prevalent of which is ozone, result from the combination of unsaturated hydrocarbons with NO_x, other reactive organics and oxygen in the presence of sunlight (OECD Transport and the Environment, 1988). These photochemical oxidants are often referred to as photochemical smog. NO_x and ozone are the best understood, and are the only photochemical oxidants presently targeted in pollution control measures (Horowitz, 1982). In addition, sulfur and NO_x can both transform in the air to produce acid deposits (OECD Transport and the Environment, 1988). Thus, NO_x and HC are primary pollutants that are also important as precursors to secondary pollutants.

3.4.2 Harmful Effects of the Pollutants

The individual emission components are harmful to varying degrees. The effects of emissions can be difficult to assess, depending on how easily a source can be traced, whether or not a causal link can be established, and how long the effects incubate before they can be seen or evaluated (OECD Transport and the Environment, 1988). It would be desirable to isolate effects to determine which sources are responsible for certain emissions. On the other hand, it is important to understand the combined effect of various emissions that act as precursors to secondary pollutants or that are more harmful when in the presence of another pollutant.

Nitrogen Oxides (NO_x)

Nitrogen oxide (NO) transforms into nitrogen dioxide (NO_2) upon emission from a motor vehicle. NO can be transformed quickly by the body and is easily detoxified (Lenz, 1994). NO_2 is responsible for respiratory irritation, and asthmatics are particularly sensitive to it (OECD Transport and the Environment, 1988). NO_2 also absorbs the full visible spectrum of light, and can reduce visibility even in the absence of other substances (Corbitt, 1990). The most important characteristic of NO_2 is that it is a ozone precursor and forms acids in combination with soot and SO_2 (Lenz, 1994).

Carbon Monoxide (CO)

CO can combine with blood faster than oxygen. Depending on the concentration of CO in the air, the lack of oxygen transported to body tissue can result in impaired coordination, vision, judgment, and aggravation of the symptoms of cardiovascular disease (OECD Transport and the Environment, 1988).

Carbon Dioxide (CO_2)

In realistic concentrations, carbon dioxide is not a health risk to humans. However, CO_2 is the major contributor in volume to the greenhouse effect. There is mounting support from third-world nations, European nations and North American insurance companies to drastically curb CO_2 emissions in an effort to reverse apparent global warming trends (Flavin, 1996). Pressure to reduce CO_2 emissions from transportation sources will likely increase in the future.

Hydrocarbons (HC)

The components of the group of hydrocarbons are primarily important as precursors to photochemical smog (Corbitt, 1990). The various hydrocarbons range in effect from being benign, as are methane, ethane, and ethene, to being carcinogenic, as are some aromatic hydrocarbons found in diesel emissions (Lenz, 1994). Motor vehicles have been found to contribute to approximately 50% of annual toxic emission cancer deaths, between 629 and 1,874 deaths annually in the U.S. (Talwar, 1992). Some of these are attributable to volatile organic compounds, or VOC's, such as benzene and butadiene.

Sulfur Dioxide(SO_2)

SO_2 easily forms acids and, under non-ambient conditions, can form strong cell poisons (Lenz, 1994). Acid deposition resulting from SO_2 emissions damages materials and has been responsible for the acidification of lakes and rivers (Corbitt, 1990).

Particulate Matter

Particulate matter can aggravate bronchitis, asthma, cardiovascular patients and influenza patients (OECD Transport and the Environment, 1988). Some of the compounds in soot are carcinogenic (Lenz, 1994). Soot particles are small enough to be inhaled deep into the lungs (Lenz, 1994). The toxic potential of SO_2 is increased in the presence of soot particles and soot is a catalyst for the formation of acids (Corbitt, 1990). These particulates are also responsible for reduced visibility and soiling of materials.

Asbestos Fibres

Some brake pads are made using asbestos fibres, which are known to be carcinogenic and can easily be inhaled (OECD Transport and the Environment, 1988).

Lead

Lead from road transport sources can be inhaled or ingested. Very low levels of lead produce neurophysiological effects; higher levels result in damage to many bodily organs and functions (OECD Transport and the Environment, 1988). The reduction in the use of leaded gasoline in the U.S. in the 1970's resulted in a parallel decline in blood lead levels (OECD Transport and the Environment, 1988).

Ozone

This photochemical oxidant is responsible for plant damage and growth rate reduction, degradation of rubber and the formation of smog (OECD Transport and the Environment, 1988). In humans it can cause susceptibility to infection and eye, nose and throat irritation (OECD Transport and the Environment, 1988). Ozone also produces clinical symptoms of respiratory illness and reduced pulmonary function (Horowitz, 1982).

3.4.3 Contribution of Motor Vehicles to Air Pollution Problems

Attempts to predict the effect of pollutants on a large scale are subject to many errors due to the aggregation of many individual vehicle factors that influence emissions. Estimates of the total contribution of highway and road traffic to overall worldwide pollution levels varies widely in the literature. Road transport may contribute 10% of total anthropogenic (man-made) emissions of CO_2 (SAE, 1994). Road transport may be responsible for 16% of total anthropogenic emissions of CO

(SAE, 1994). It has been estimated that 50% of ozone precursors come from sources in the transport sector (OECD Transport and the Environment, 1988). As an example of how wide the range of estimates may be, the contribution of the transport sector to total anthropogenic emissions of NO_x could be between 30% (SAE, 1994) and 60% (OECD Transport and the Environment, 1988). None of these figures, which are often quoted in the literature, account for concentrations near densely populated areas.

Motor vehicle traffic, then, is responsible for a significant portion of the total anthropogenic levels of these pollutants. Natural sources create much higher levels of these pollutants, but do not result in air quality problems in urban areas. Without the addition of anthropogenic sources, background levels of primary air pollutants would be well below air quality standards (Horowitz, 1982). Although levels vary from city to city, nearly all CO and approximately half of all NO_x and HC emissions in urban areas can be attributed to motor vehicles. Motor vehicle traffic pollution poses a serious health problem because it is concentrated near human habitats. With the exception of CO_2, which is of concern as a greenhouse gas, the concentration of pollutants in urban areas is of primary concern.

3.4.4 Future Emission Trends

As discussed in Chapter 5, substantial improvements to individual vehicle emissions have been made to automobiles since 1980 and to most other motor vehicles since the mid-1980's. Many years must pass before a rollover in the vehicle fleet can occur. As a result, there may be an improvement in emissions simply due to the passing of time. Despite an increase in vehicle miles traveled, between 1982 and 1991 volatile organic compounds have decreased by 46%, CO emissions have decreased by 45%, and NO_x emissions have decreased by 32% (Shrouds, 1994). These decreases can be attributed to improved vehicle technology, improved fuel economy, cleaner-burning fuels, and improved inspection and maintenance programs (Shrouds, 1994). Continued decreases in these emissions by the road transport sector can only be expected into the early part of the next century, when the rapidly increasing number of vehicle miles traveled will force an increase in overall emissions (Shrouds, 1994). Increases in the number of goods vehicles signal that attention should be concentrated on diesel emissions (OECD Transport and the Environment, 1988). Although the use of new fuel technologies in developed countries will grow, it is recognized widely that use of gasoline powered automobiles and diesel powered trucks will continue to grow and will remain the primary mode of highway transport due to the demographic characteristics of North American urban areas.

3.4.5 Addressing the Air Pollution Problem

Air quality management has become an important priority for metropolitan transportation authorities, particularly in the United States. The CAAA and ISTEA mandate compliance with strict air quality standards. Considerable effort is now spent in predicting air quality impacts of transportation planning decisions and in determining emissions inventories for urban areas. Two emission models are presently used for these purposes: the Environmental Protection Agency's MOBILE model, and the California Air Resources Board's EMFAC model. As well, new modal emission models are being developed to improve the accuracy of inventory assessments and to meet more detailed demands for predictive ability necessary to evaluate different transportation alternatives.

The Clean Air Act Amendments of 1990 (CAAA) require non-attainment areas to reach attainment by certain specified dates (Stephenson and Dresser, 1993). Non-attainment areas are urban regions that exceed the pollution levels that are described in the National Ambient Air Quality Standards (NAAQS). A region can be designated a non-attainment area for specific pollutants including lead, CO, ozone and PM-10. Since transportation emissions make up such a significant portion of total emissions as shown previously, achieving attainment requires action on the part of metropolitan transportation organizations. This action is known as transportation conformity. Rules laid out by the EPA and the FHWA are often referred to as air quality conformity rules (Stephenson and Dresser, 1993). Transportation plans, programs and projects must adhere to the goals of the State Implementation Plan (SIP) to meet conformity. This involves qualitative assessment of plans, quantitative assessment of programs, and analysis of the local CO impacts of projects (Stephenson and Dresser, 1993). Tools for the analysis of plans and programs are regional models (MOBILE and EMFAC), while reliable tools and data collection schemes for more detailed analysis are in development. These tools, modal emission models, are discussed in more detail in Chapter 5.

A major requirement of the CAAA is that emission inventories are required for ozone and CO non-attainment areas. The current version of the MOBILE model is required for this inventory (Stephenson and Dresser, 1993). California is permitted to use the EMFAC model because their vehicles adhere to tighter emission controls and the EMFAC model has been demonstrated to perform as well as the MOBILE model. Emission inventories must be updated year-to-year to determine if milestones for VOC, NO_x and CO are being met and to demonstrate that ozone non-attainment areas are making Reasonable Further Progress (RFP) towards specific reductions in ozone levels. Again, the MOBILE or EMFAC models are used to determine these inventories.

Mobile Source Emission Models

As mentioned above, the MOBILE and EMFAC models are used widely today to predict emissions in urban areas. These two models are known as speed factor models. The emission tests on which the models are based have been aggregated; a vehicle's emissions are modelled such that they depend only on the average speed of the vehicle between long sections of a road network. In other words, the time a vehicle spends accelerating, decelerating, cruising and idling would not influence the emissions predicted by these two models. Air quality analysis now demands that this modal activity be taken into account. As a result, there are new models known as modal emission models under development today.

Modal Emission Models

Two major modal emission models will be available in the late 1990's. A project at the Georgia Institute of Technology is being funded by the EPA, and a separate project at the University of California at Riverside is being funded by the National Cooperative Highway Research Program (NCHRP). Both projects will lead to vehicle emission models that account for accelerations, decelerations, cruising and idling of vehicles. The models will also be based on a more realistic series of tests than the current emission test database.

Dispersion Models

The dispersion of pollutants generated by motor vehicles is typically modelled separately from the emissions. Gaussian plume models are widely used even though they involve many simplifications and cannot incorporate prediction of the formation of secondary pollutants like ozone or sulfuric acid (Hassounah and Miller, 1994). Future enhancements of the approach may involve incorporating Geographic Information Systems into statistical models of pollutant concentrations (Hassounah and Miller, 1994).

Fuel Consumption Models

Fuel consumption is correlated with emission rates. This suggests that fuel consumption can be used to model the rate of emissions. However, with the exception of the emission of CO_2, the relationship between the two rates is complex.

CO and HC, for example, are products of the incomplete combustion of fuel, and depend on the fuel volatility, the engine and catalytic converter temperature, and the whether the vehicle is fuel injected or carbureted. The emission of CO and HC is not likely to be directly correlated with fuel consumption. HC emissions would likely be lower if fuel economy was improved, since evaporative emissions associated with refueling would be reduced (Guensler, 1994). NO_x emission is likely to decrease with the amount of fuel consumed (Hassounah and Miller, 1994). Sulfur, on the other hand, is regularly assumed to be fully converted to SO_2 in the combustion process. The emission of SO_2 can be estimated with a model of fuel consumption.

3.5 Assessing the Costs of Noise and Air Pollution

The estimation of benefits and costs has become a priority in many fields. The use of cost-benefit analysis is often encouraged as a way to guide decisions involving high risks (Mishan, 1988). As a result, the quantification of benefits and costs has received a great deal of attention in economics. This section explores methods of determining the costs of air and noise pollution. The section is divided into three parts: the first is a brief overview of the theory and methods of quantifying benefits and costs, the second is an explanation of the problems with the estimates, and the third is a summary of the estimates used later in this thesis.

3.5.1 How Costs and Benefits Are Quantified

The costs and benefits of many actions are unclear. Some things, including a quiet environment and clean air, do not have explicit markets. Economists attempt to quantify the value that people place on these things using a variety of methods. The methods all involve an attempt to discover people's willingness to pay for reductions and/or increases in the amount of something. For example, because clean air is not openly traded for money, and there are no lines between what one person owns and what another owns, economists look at other transactions that people make involving clean air to estimate their willingness to pay for an improvement in the pollution level in a city. Two methods of determining the willingness to pay are discussed here: direct and indirect approaches.

Direct approaches involve eliciting the willingness to pay from survey respondents by confronting them with a hypothetical scenario (Shechter and Kim, 1991). The contingent valuation method is one such approach. Survey respondents are presented different hypothetical scenarios and their willingness to pay is directly reported. For example, a person would be asked how much he or she would be willing to pay for a reduction in the amount of air pollution in his or her community. This approach depends on the response of individuals to questions in the form of a survey, which does not necessarily represent their actions in a realistic situation Another such approach is the contingent ranking method. This method is a variation of the contingent valuation method, and also involves surveys. The individual's ranking of different goods, including pollution abatement, is input to a utility model.

In this model, a change in the individual's income is required to offset the change in the level of the good. The individual's willingness to pay for the good is derived from this change in income (Cummings et al., 1986). The contingent valuation and ranking approaches are useful for examining scenarios that are outside the realm of possibility in the present, such as the impact of a road that might be constructed in the future (Adamowicz, 1994). The valuation of environmental quality has been shown to be consistent from study to study, however, and has also been shown to agree with the results of revealed preference surveys, discussed below (Farber and Rambaldi, 1993). A recently developed approach known as the petition method may gain future acceptance (Cummings et al., 1986). The petition method involves, for instance, surveying individuals' willingness to sign a petition calling for a reduction in the level of pollution with certain monetary costs to be borne by the individual. The advantage of this method over the contingent valuation and ranking methods is that the petition is not based on a merely hypothetical change in pollution levels (Cummings et al., 1986).

Indirect approaches involve using the market behavior of people as a surrogate for their valuation of an immeasurable benefit. A widely applied indirect monetary method is the hedonic price method. Market prices of private goods that are affected by a change in the level of pollution are used to derive people's willingness to pay (Cummings et al., 1986). For example, an increase in the level of traffic noise in a community might result in a decrease in property values of homes affected by the noise. Regression models may be applied to the housing market data to derive an estimate of how much people in the community and potential homeowners value a quiet living environment. The strength of this indirect approach is that it is based on actual behavior rather than hypothetical scenarios.

3.5.2 Obstacles to Acceptance of Derived Values

Aside from practical problems involved in applying the above methodologies, there are general issues that render uncertain the results of both direct and indirect approaches. Many assumptions must be made to estimate the value of reduced risks using the above methods. First, there must be alternatives to accepting the risk (Juas and Mattsson, 1987). This may not be the case for residents subjected to noise and air pollution. Residents may find it difficult and financially and emotionally demanding to relocate after a change in the level of air or noise pollution (Walters, 1975). Second, the decision-maker must be informed of all of the relevant facts and their dimensions (Juas and Mattsson, 1987). In the case of air pollution, a resident may not attribute their stress to traffic noise levels, or may not attribute their increased risk of lung cancer to vehicle emissions. Third, the decision-maker must be expected to act rationally and make the same decision each time under the same circumstances (Juas and Mattsson, 1987). For example, a resident ideally would assess the value of a reduction in traffic noise levels the same every time he or she was surveyed; this is a requirement that is difficult to address. The uncertainty involved in validating these three assumptions makes the results of benefit studies somewhat suspect (Walters, 1975).

In addition, there are major problems with measuring the willingness to pay of individuals. First, it is very difficult to assess the willingness to pay for incremental changes in pollution levels (Freeman, 1979). There are many other influences and variables that affect a person's willingness to pay. Changes in pollution levels must be charted separately from these variables. Second, often economists must report their benefit findings as either *at most* or *at least* values, because so many levels of benefits, such as money, time, convenience, comfort, and peace of mind, can be included in the reported value of a reduction in pollution (Juas and Mattsson, 1987). Third, it is difficult to measure all of the benefits of a reduced risk in an entire system (Juas and Mattsson, 1987). For example, an increase in traffic noise might result in people double-glazing their windows or keeping them shut all the time, a cost that might not be reflected in the property value. Fourth, the individual risks to people must all be separated (Juas and Mattsson, 1987). Because of the numerous influences on an individual's psyche, identifying the contribution of noise levels alone to people's stress is very difficult.

There are other assumptions that are particular to each of the methods described above (Cummings et al., 1986). Because of these issues, values for the benefits of air and noise pollution abatement are full of uncertainty. Future success may be found in combining the approaches discussed above, both to validate each method's results and to complement the costs accounted for in each method (Adamowicz, 1994). At present, it may be argued that these costs could be used to guide decisions, but not to make decisions. It becomes difficult, then, to identify the particular costs that should be allocated to vehicles. The issue of identifying the benefits of air and noise pollution is not the concern of this thesis; however, finding acceptable measures of benefits may be a major obstacle to the full implementation of externality pricing.

3.5.3 Costs of Noise and Air Pollution Used for this Analysis

Despite the promise of future work, there is no agreement on specific values for the cost of noise and air pollution. A portion of this thesis, however, includes a demonstration of the allocation of costs associated with air and noise pollution. Solely for the purposes of illustrating the allocation methodology, representative values for these costs are used in the example problem in this thesis. The cost of constructing noise barriers is used to represent the costs of noise, and a general figure for the cost of air pollution in the U.S. is used to represent the costs of air pollution (Tellis and Khisty, 1995).

3.6 Conclusions

In this chapter, the following were shown:

1. Road pricing is a feasible method of Direct Demand Management. Incorporating noise and air pollution costs into congestion pricing schemes is possible.

2. There are equity concerns that must be addressed in the implementation of a road pricing scheme and in the allocation of the costs of noise and air pollution among

road users. These equity concepts include the assessment of fair and justified charges (formal equity) and attention to the affects of charges on the distribution of resources among societal groups (distributional equity). Equity concepts applied to the allocation of pavement costs can be extended to the allocation of the costs of noise and air pollution among road users. These concepts include the notions of Completeness, Rationality and Marginality. The costs of noise and air pollution are shown to be Joint Costs best allocated using the Occasioned Cost approach.

3. Different noise measurement indices are used to describe sound levels as they are interpreted by [illegible] The most common such levels are the equivalent sound unit, Leq, and the mean sound interval exceeded n percent of the time, Ln. The generation of noise from motor vehicles is most frequently predicted using empirical models.

4. The emission of numerous pollutants from motor vehicles is a major concern in urban areas, particularly in the U.S., where transportation improvements must now conform to the requirements of the CAAA and ISTEA before approval. The MOBILE emission model is widely used throughout North America to predict motor vehicle emissions, although improved modal emission models will be completed by the year 2000.

5. Direct and indirect methods of determining people's willingness to pay for noise and air quality improvements yield uncertain results. Consequently, there is no

agreement on the costs of noise and air pollution that should be assessed to road users.

Chapter 4

Measures of Responsibility for Noise

4.0 Introduction

This chapter, along with Chapter 5, focuses on examining a method for identifying responsibility for environmental costs based on engineering criteria. The environmental disbenefit examined in this chapter is noise pollution. A brief overview of noise pollution models is presented. A noise responsibility measure is then calculated for a variety of vehicle classes that use the transportation system. Lastly, an example problem is used to illustrate how the costs associated with a pollutant may be assigned to the individual vehicles within a traffic stream based on their associated responsibility.

4.1 Traffic Noise Prediction and Factors Influencing the Generation of Noise

4.1.1 Traffic Noise Prediction Modelling

There are a variety of traffic noise prediction models that are used worldwide for assessing the potential noise levels for new roadways or noise levels in the future due to traffic increases. There are essentially three different ways to approach the prediction of traffic noise. One method is to build scale models to recreate the area of interest and measure the noise produced by miniature sources (Favre, 1987). Alternatively, theoretical models may be derived which predict noise levels based on such variables as sound intensity and distances from sources (Takagi et al., 1974).

The most widely used method of traffic noise prediction is empirical modelling that is based on measurements of noise in the field. This chapter presents a comprehensive overview of empirical models in use in North America and Europe. All the models that are examined attempt to relate the overall noise level emanating from one or more road segments based on their respective physical attributes and traffic characteristics. The unit of noise in the models is the decibel (dB) and the dependent variable in the models is either the sound level L_{10} or the equivalent continuous sound level, L_{eq}. The noise from the road segment is assumed to be generated from a line source.

All of the noise prediction models have a general linear additive form as shown in Equation 4-1. In the models examined there were 12 variables identified as affecting traffic noise and these variables can have a linear or logarithmic affect on the sound level. An overview of the different models and the relevant variables is presented in the following sections.

[4-1]

$$L_x = A + \sum_{i=1}^{n} B_i \log_{10} X_i + \sum_{j=n+1}^{m} B_j X_j + \sum_{i=1}^{n} \sum_{j=n+1}^{m} B_{ij} f(X_i, X_j)$$

where	x	sound level descriptor: eq, 10, 50, or 90
	A, B_i, B_j, B_{ij}	constants derived from field samples
	X_i, X_j	variables that influence noise level at receiver.

and $f(X_i, X_j)$ an interaction term used only in Model 1.

The models examined in this chapter may be divided into two distinct groups: those for prediction of noise from arterials and those for highways. The latter are generally used when the average traffic speed is above approximately 50 km/h. The former are generally used to predict noise in interrupted flow conditions when the average traffic speed is below approximately 50 km/h. The models may be further classified based on the dependent variable, either L_{eq} or L_{10}. For each model, the parameters are defined and the range of values used by the author in the calibration process, if provided, is shown.

4.1.2 Uninterrupted Flow (High Speed) Models

Model 1 is often referred to as the UK DoE model. It was developed by researchers at the Department of the Environment in Britain and was adopted for use in England, Wales and Australia in 1975 (Delany et al., 1976). Prior British noise prediction models were only useful in specific situations. Model 1 was created to predict noise levels in as many cases as possible and in both free flow and interrupted flow regimes. Average speed, vehicle flow, percentage of vehicle types, road grade and road surfacing were identified as contributing to the overall noise production. The interaction between the percentage of heavy vehicles and the average speed is modelled explicitly. As defined in this model, light vehicles weigh less than 1525 kg and heavy vehicles weigh more than 1525 kg.

Model 1: Equation [4-2]

$$L_{10} = 10\log q + 33\log(V + 40 + \frac{500}{V}) + 10\log(1 + \frac{5p}{V}) - 27.6 + \text{corrections}$$

where:

V mean speed (km/h). Range: 45 - 100 km/h.

p percentage of vehicles over 1525 kg (unladen). Range: 2 - 60%.

q mean hourly flow (veh/h). Range: 350 - 3500 vph.

Corrections (i.e. - ΔL_{10}):

i) gradient
= 0.2 G where G = gradient.

ii) deep random grooving on road
= 4 - 0.03p where p = percent heavy vehicles.

iii) distance from source
= -10 log (d '/13.5) ①
or
= -10 log (d '/13.5) + 5.2 log [3h(d + 3.5)] ②
where d ' = slant distance from source.
d = distance from kerb
h = height of receptor above ground.
Equation ① is used if ground is hard or if 1=<h=<(d+3.5)/3
Equation ② is used if h >=(d+3.5)/3

iv) uneven ground
= 2H - 0.5 where H = average height of propagation path above ground.

v) facade effects
= 2.5 dB for a house-lined street.
= 1.0 dB for further continuous, high, unbroken containment.

vi) retained cut
$= Ye^{(-0.019\Phi^2)}$ where Y = depth of cut in metres

and ϕ = angle of walls to vertical in degrees.

vii) barrier

viii) angle of view

Model 2 was developed in Ontario (Hajek and Krawczyniuk, 1983). This model purposely included only four basic variables: average speed, volume, traffic composition and the distance from the source to the receiver. The objectives of developing the model were to estimate the maximum accuracy possible using only these basic variables and to compare the results with those of existing models to help select a noise prediction program for the use of the Ontario Ministry of Transportation and Communications. The model was useful in illustrating that the inclusion of these four variables alone provides very limited accuracy, and it was suggested that as many propagation and generation variables as possible should be included in noise prediction models (Hajek and Krawczyniuk, 1983). The speed of the vehicles and the number of vehicles in each vehicle class were identified as the principle noise production variables. Light vehicles are defined as automobiles, medium trucks are vehicles with two axles and four tires on the rear axle, and heavy trucks are vehicles with three or more axles.

Model 2: Equation [4-3]

$$L_{eq} = 21.5 + 11.1\log_{10}(V_c + 10V_{mt} + 15V_{ht}) - 15.4\log_{10} D + 15.0\log_{10} S$$

where

V_c volume of cars (veh/hour).

V_{mt} volume of medium trucks (veh/hour).

V_{ht} volume of heavy trucks (veh/hour).

D equivalent distance, the square root of the product of the perpendicular distance between receiver and centrelines of near and far lanes (m).

S average operating speed of traffic flow during an hour (km/h).

Equation 4-4 describes the original STAMINA prediction model, referred to here as Model 3. The STAMINA program was originally created in 1977 as the FHWA Highway Traffic Noise Prediction Model to handle complex cases of noise prediction Barry and Reagan, 1977). An improved model created at the Pennsylvania State University for the FHWA, the Penn State University Highway Transportation Noise Model (PSUHTRAN), is also based on the STAMINA equations shown below (Lawther, 1985). STAMINA Version 2.0 is used by jurisdictions throughout the United States and in Ontario. The program uses Reference Energy Mean Emission Levels, or REMELS, for different vehicle classes as the core of the model. Some examples of different REMELS are:

a. Original FHWA (Barry and Reagan, 1978)

b. FHWA Four-State: Colorado, Florida, N. Carolina, Washington

(Rickley et al., 1978)

c. Florida (Dunn and Smart, 1986)

d. Florida (Wayson et al., 1993)

e. Ontario (Jung and Blaney, 1988).

In STAMINA models, light vehicles are defined as having 2 axles, 4 wheels, and weighing less than 4,500 kg. Medium vehicles are defined as having 2 axles, 6 wheels, and weighing between 4,500 kg and 12,000 kg. Heavy vehicles have 3 or more axles and weigh over 12,000 kg.

Model 3: Equation [4-4]

$$L_{eq}(\text{overall}) = 10\log\left(10^{L_{eqA}/10} + 10^{L_{eqMT}/10} + 10^{L_{eqHT}/10}\right)$$

where:

L_{eq}(A, MT or HT) = REMEL$_{A,\ \ \ \ \ HT}$ + flow, distance, road segment

and

shielding corrections

REMELS are show

flow correction = 10 .

where:

N_i	number of vehicles of class i passing in an hour.
S_i	speed of vehicles in class i (km/h).
D_o	15 m , the distance between the line of traffic and the point at which the REMEL was measured.

distance correction $= 10\log\left(\frac{D_o}{D}\right)^{1+\alpha}$ for hard ground.

$= 15\log\left(\frac{D_o}{D}\right)^{1+\alpha}$ for soft ground.

where:

D distance between the observer and the centre of the travel lane (m).

D_o 15 m , the distance between the line of traffic and the point at which the REMEL was measured.

α a site condition parameter.

road segment correction $= 10\log\left(\frac{\Delta\phi}{\pi}\right)$ for hard ground.

$= 10\log\left(\frac{\psi_{1/2}(\phi_1,\phi_2)}{\pi}\right)$ for soft ground.

where:

ϕ_1, ϕ_2, $\Delta\phi$ angles swept from the perpendicular between the observer and the highway and the ends of the highway segment.

shielding correction

- dense woods and rows of houses: the noise loss due to a number of scenarios is given.
- barriers: detailed calculations are required.

Table 4-1. REMELS for Use with Models 3 and 4

Location/Authors/ Year	**Reference E[illegible]gy Mean Emission Levels (REMELS)**		
	Automobiles	**Medium Trucks**	**Heavy Trucks**
U.S. / FHWA / 1978	38.1 log S - 2.4	33.9 log S + 16.4	24.6 log S + 38.5
Four U.S. States / Rickley et al.- FHWA / 1978	38.1 log S(mph) + 5.47	33.9 log S(mph) + 24.4	24.6 log S(mph) + 46.58
Florida / Dunn and Smart / 1986	32.283 log S + 10.803	23.221 log S + 36.129	14.058 log S + 56.234
Florida / Wayson et al. / 1993	31.130 log S + 12.777	18.765 log S + 43.697	12.831 log S + 58.270
Ontario / Jung and Blaney / 1988	Only published in modified form.		

Model 4 is a simpler version of the original STAMINA program and was designed for use on personal computers (Jung and Blaney, 1988). The modification in Model 4 involved changes to methods of calculation that make the program simpler and quicker. The modifications make it easy to replace REMELS for different vehicle types in different jurisdictions or different years. Vehicle noise measurements were taken in 1984 and 1985 in Ontario to calibrate this model.

Model 4: Equation [4-5]

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

where:

V volume of traffic (veh/hour).

D_E equivalent lane distance, average of distance to nearest and furthest lane (m).

Φ equivalent subtending angle: $\Phi = 180 / 1 + 0.58\alpha^{0.9}$ if view unobstructed.

α land dampening coefficient.

$$K = \frac{NA}{442.53V} S_A{}^{2.81} + \frac{NMT}{5.83V} S_{MT}{}^{2.39} + \frac{NHT}{3.59721 \cdot 10^{-2} V} S_{HT}{}^{1.46}$$

where

V total volume of vehicles (veh/hour).

N_A, N_{MT}, N_{HT} number of automobiles, medium trucks and heavy trucks in the flow (veh/hour).

S_A, S_{MT}, S_{HT} average speed of automobiles, medium trucks and heavy trucks (km/h).

Models 5 and 6 were developed in Great Britain (Jraiw, 1990). The impetus for the development of Models 5 and 6 was the transition to the use of the noise level L_{eq} as the basis for evaluating noise in Britain. No definition of the vehicle classes was given.

Model 5: Equation [4-6]

$$L_{eq} = 56.50 - 6.53\log_{10} V + 11.6\log_{10} Q + 0.17P - 6.48\log_{10} F - 0.01J - 2.47\log_{10} N$$

Model 6: Equation [4-7]

$$L_{10} = 58.60 - 5.99\log V + 11.40\log Q + 0.18P - 5.94\log F - 0.0102J - 2.46\log N$$

where

V mean speed of traffic (km/h). Range: up to 80 km/h in outer urban areas.

Q traffic flow (veh/hour).

P percentage of medium and heavy vehicles (%). Range: 0 to 20%.

F distance between measurement point and farside building facade (m).

J distance from the relevant junction (m).

N distance between measurement point and nearside facade (m).

4.1.3 Interrupted Flow (Low Speed) Models

Model 7 was developed in Great Britain by the Transport and Road Research Laboratory (Gilbert et al., 1980) and is shown in Equation 4-8. This model is often referred to as the TRRL model. This model was developed because the UK DoE method, Model 1, was shown to overpredict noise levels in interrupted flow conditions. Since the primary vehicle flow regime in urban areas is interrupted flow, it was seen as necessary to create a more reliable model for predicting L_{10} in urban areas. Surveys and measurements were taken primarily in London and Edinburgh. Only the number of vehicles in each vehicle class are identified as affecting the noise production. Light vehicles are defined as cars, vans and light goods vehicles weighing less that 3000 kg. Medium vehicles are defined as vehicles with 2 axles, including buses and coaches, weighing more that 3000 kg. Heavy vehicles are defined as commercial vehicles with 3 or more axles.

Model 7: Equation [4-8]

$$L_{10} = 43.5 + 11.2\log_{10}(L + 9M + 13H) - 0.42c - 10.2\log_{10}\left(\frac{d_k + 3.5}{4.5}\right)\delta_1$$
$$+4.6\log_{10}\left[1 + \left(\frac{d_k + 3.5}{d_k + 3.5 + 2(d_f - d_k)}\right)\delta_2\right]$$

where:

L	numbers of light vehicles (veh/hour).
M	numbers of medium vehicles (veh/hour).
H	numbers of heavy vehicles (veh/hour).
d_f	distance from the kerb to the nearside building facade (m).
d_k	distance from the kerb to the receiver (m).
c	width of the carriageway (m).
δ_1	$= 1 + 0.52p_1$ where p_1 = proportion of soft ground in distance d_k.
δ_2	$= 1 + 0.52p_2$ where p_2 = proportion of soft ground in distance $d_f - d_k$.

Model 8 is the product of joint research between the Instituto di Acustica in Italy and the Technische Universitat Munchen in West Germany with the purpose of developing a prediction method for Italian towns (Cannelli et al., 1983). The model structure is shown in Equation 4-9. This method was then used to create noise contour maps for planning and regulatory purposes and to correlate noise levels with demographic characteristics in the towns. The empirical measurements for the model were made between March 1979 and October 1980. Light vehicles were defined as private cars and commercial vehicles weighing less than 4,800 kg, and heavy vehicles are defined as heavy commercial vehicles and public transport vehicles weighing over 4,800 kg. In addition to the velocity and number of vehicles in each vehicle class there were three additional variables that were identified as affecting noise generation - road surfacing condition, road gradient, and congestion.

Model 8: Equation [4-9]

$$L_{eq} = \alpha + 10\log_{10}(N_L + \beta N_W) + 10\log_{10}\frac{d_o}{d} + \Delta L_V + \Delta L_F + \Delta L_B + \Delta L_S + \Delta L_G + \Delta L_{VB}$$

where:

α, β constants: 35.1 and 8, respectively, for Italian towns.

N_L flow of private cars, normal motorcycles and light commercial vehicles (veh/hour). Range: 0 to 2500 veh/hour.

N_W Flow of heavy commercial vehicles, public transport vehicles, and high noise level motorcycles (veh/hour). Range: 0 to 400 veh/hour.

d distance from centre of traffic flow (m).

d_o standard distance d = 25 m.

ΔL_V flow velocity correction (dB (A)). Range: 30-50 km/h $\Rightarrow$ 0, 100 km/h $\Rightarrow$ +4.0.

ΔL_F reflection by nearside building facade correction (dB (A)), 2.5.

ΔL_B reflection by farside building facades (dB (A)), 1.5.

ΔL_S road surfacing correction (dB (A)). Range: smooth asphalt $\Rightarrow$ -0.5, pavement $\Rightarrow$ +4.0.

ΔL_G road gradient correction (dB (A)). Range: =< 5% ⇒ 0, 10% ⇒ +3.0 .

ΔL_{VB} factor to correct for extreme traffic conditions (dB (A)). Range:
near signals ⇒ + 1.0 , flow velocity < 30 km/h ⇒ -1.5 .

Model 9 and Model 10 are interrupted flow models developed in Great Britain to fulfill a perceived need for more attention to noise prediction of low speed traffic in urban centres (Jraiw, 1990). The dependent variable in Model 9 is the L_{10} while the dependent variable in Model 10 is the L_{eq}. It should be noted that the L_{eq} is the current measure of noise pollution in Great Britain. The principle noise source variables are the speed of the vehicles and the number of light, medium and heavy vehicles. The structure of Models 9 and 10 and Models 5 and 6 is very similar with the primary difference that former uses the number of each vehicle type while the latter uses the total volume and percentage of each vehicle type. Note that no definition of heavy, medium or light vehicles was found in the literature although it is assumed that th classes are equivalent to those of Model 3. The rest of the parameters are related to noise propagation.

Model 9 - Equation [4-10]

$$L_{eq} = 54.90 - 6.11\log_{10} V - 5.51\log_{10} F - 0.01J - 11.70(L + 6M + 10H) - 4.01\log_{10}(d - k)$$

Model 10 - Equation [4-11]

$$L_{10} = 57.00 - 5.60\log_{10} V - 5.39\log_{10} F - 0.01J + 11.70(L + 6M + 10H) - 4.00\log_{10}(d - k)$$

where:

V	mean ced of traffic (km/h). Range: up to 50 km/h in inner urban areas.
F	distance between measurement point and far side building facade (m).
J	distance from the relevant junction (m).
L	number of light vehicles / automobiles (veh/hour).
M, H	number of medium and heavy vehicles (veh/hour).
d	distance between nearside kerb and nearside facade (m).
k	distance between measurement point and nearside kerb (m).

The ten models are summarized in Table 4-2 below.

Table 4-2. Traffic Noise Prediction Models

Model #	Common Name	Authors	Origins	Year	Speed Regime
1	U.K. DoE	Delany et al.	United Kingdom	1975	High
2	-	Hajek and Krawczyniuk	Ontario	1983	High
3	STAMINA (five calibrations shown below)	Barry and Reagan	U.S.	1977	High
3a		Barry and Reagan	U.S.	1978	
3b		Rickley et al.	Four U.S. states, including Florida	1978	
3c		Dunn and Smart	Florida	1986	
3d		Wayson et al.	Florida	1993	
3e	(compatible with STAMINA; published with Model 4)	Jung and Blaney	Ontario	1988	
4	Modified STAMINA	Jung and Blaney	Ontario	1988	High
5	-	Jraiw	United Kingdom	1990	High
6	-	Jraiw	United Kingdom	1990	High
7	TRRL	Gilbert et al.	United Kingdom	1980	Low
8	-	Cannelli et al.	Italy	1983	Low
9	-	Jraiw	United Kingdom	1990	Low
10	-	Jraiw	United Kingdom	1990	Low

4.1.4 Noise Generation Variables

The noise level predicted by each model is determined by factors influencing both the generation and propagation of sound between the source and the receiver. Table 4-3 shows the factors that affect noise generation and whether they are taken into account by the models. It may be seen in Table 4-3 that traffic flow is a noise generation factor that is common to all of the models. This would be expected as increases in the rate of vehicle flow would naturally increase the noise level. All of the models relate flow to the noise level with the term, C log (vehicle flow), where the constant C is between [illegible] 11.7. This implies that the noise level rises at a decreasing rate as ve[illegible] flow increases; this effect is consistent across all of the models.

Table 4-3. Traffic Noise Generation Factors

Range and Sound Level	Model	Flow	Speed	Vehicle type	Gradient	Road Surfacing	Proximity to Junction
High Speed L_{eq}	Model 2	Y	Y	Y			
	Model 3	Y	Y	Y			
	Model 4	Y	Y	Y			
	Model 5	Y	Y	Y			Y
High Speed L_{10}	Model 1	Y	Y	Y	Y	Y	
	Model 6	Y	Y	Y			Y
Low Speed L_{eq}	Model 8	Y	Y	Y	Y	Y	Y
	Model 9	Y		Y			Y
Low Speed L_{10}	Model 7	Y		Y			
	Model 10	Y		Y			Y

The effect of the average traffic speed on the noise level depends on the speed at which the components of a vehicle are operating. Five basic noise sources on a vehicle have been identified and these may be classified on the basis of speed dependency: engine, exhaust, induction, fan, and tire noise (Tyler, 1987). Engine, exhaust, induction and fan noise are generally considered speed independent even though they are related to engine speed (Favre, 1987). The reason for this assumption is that there is a wide range of gear ratios in diesel trucks (which dominate overall noise levels); this ensures that there is a relatively narrow range of engine speed. It has been found that tire noise is speed dependent and tire noise is considered the dominant noise source at speeds over 100 km/h for almost all vehicles (Tyler, 1987).

The result of the above facts is that traffic noise only increases with speed in a certain range. When the average speed is above 50-60 km/h and the traffic is moving under free-flow conditions, most of the models examined predict the noise level to increase as the vehicle speed increases. The exceptions are Models 5 and 6 which model traffic noise decreasing with speed as evidenced by the negative coefficient in Equations 4-6 and 4-7. It was argued in the paper that introduced Models 5 and 6 that this relationship is expected because the decrease in noise to the increase in space between vehicles at higher speeds is more significant than the corresponding increase in the individual vehicle noise level. The models that predict noise for speeds below 50-60 km/h and interrupted flow conditions basically assume that the noise level is independent of the average speed. As shown in Table 4-3, the only interrupted flow regime model to include speed as a significant variable is Model 8; in this case the speed variable is simply a correction for speeds in the uninterrupted flow regime above 50 km/h. The noise level is predicted to increase 1 dB for every 10 km/h increase in vehicle speed over 50 km/h. Instead of including a speed term in the equation, which is designed for low speed scenarios, the authors transformed the continuous function between speed and noise into categories between 50 and 100 km/h so that the equation could be used in high speed scenarios (Cannelli et al., 1983). The relationship between speed and noise is futher complicated by the interaction between speed, flow and the percentage of heavy vehicles, as is discussed below.

It may also be seen in Table 4-3 that the distribution of the different vehicle types has an affect on the noise generation in all of the models investigated in this chapter. Models 1, 5, 6 and 8 divide vehicles into two categories, heavy vehicles and light vehicles, while Models 2, 3, 4, 7, 9 and 10 divide vehicles into three categories, light, medium and heavy vehicles. All of the models predict that the addition of a single heavy vehicle to the flow increases the noise level more than the addition of a single light vehicle to the flow.

There are differences, however, in the definition of a heavy vehicle, as shown in Table 4-4. Model 1 designates vehicles over 1525 kg to be heavy vehicles and has a term in its equation relating this to the overall noise level, "10log(1+5p/v)", where p is the percentage of heavy vehicles in the flow (Delany et al., 1976). The authors of Model 2 designate any two-axle truck with four tires on the rear axle a medium truck and designate any truck with three or more axles a heavy truck. The weight of this category of heavy trucks ranges from 12 000 to 65 000 kg (Hajek and Krawczyniuk 1983). A set of terms and weighting coefficients are used in the equation to relate these categories to the noise level in the form "L + 10M + 15H", where L, M and H are the numbers of light, medium and heavy vehicles passing the receiver in a given time.

Table 4-4. Classification of Vehicles in Noise Prediction Models

Model #	*Light Vehicles*	*Medium Vehicles*	*Heavy Vehicles*
1	less than 1,525 kg	-	over 1,525 kg
2	2 axles, 4 wheels	2 axles, 6 wheels	3 or more axles
3	2 axles, 4 wheels, less than 4,500 kg	2 axles, 6 wheels, between 4,500 and 12,000 kg	3 or more axles, over 12,000 kg
4	2 axles, 4 wheels, less than 4,500 kg	2 axles, 6 wheels, between 4,500 and 12,000 kg	3 or more axles, over 12,000 kg
5	n/a	-	n/a
6	n/a	-	n/a
7	cars, vans, light trucks less than 3000 kg	2 axles, over 3000 kg	3 or more axles
8	less than 4,800 kg	-	over 4,800 kg
9	n/a	n/a	n/a
10	n/a	n/a	n/a

n/a not available
- only two categories

The effect of the percentage of heavy or medium vehicles on the noise level heard by the receiver depends on the average speed of the traffic. At low speeds, because engine noise is the primary sound produced by the traffic, the loud exhaust noise generated by heavy trucks can dominate the overall noise level (Favre, 1987). At higher speeds, wind, mechanical and tire/road noises are similar in both automobiles and trucks. These start to become the primary sounds generated by the traffic stream, and most vehicles move into the same high gear. Thus, the contribution of heavy trucks to the noise level at high speeds is smaller in proportion to their contribution at low speeds . However, even at speeds of up to 110 km/h, an individual truck still contributes more to the overall noise level than an individual car. These differences in treatment of traffic composition are the basis for further investigation of these parameters later in this chapter.

The proximity to a junction, the last column in Table 4-3, is related to engine loading as a factor influencing noise generation. The level of noise generated near intersections tends to be high because of the acceleration of vehicles and the resultant high engine loading. In addition, signalized intersections produces "pulsing" of the line of traffic, which, depending on the rate of traffic flow, can significantly increase noise levels (Favre, 1978). Thus, Models 5, 6, 8, 9 and 10 incorporate a factor for the distance from the receiver to a junction.

Other factors that influence the generation of noise at the source are the road gradient and road surface. It may be seen in Equation 4-2 that as the gradient increases the greater the engine loading and the higher the noise level (Delany et al., 1976).

At high speeds, the tire/road interface becomes more prominent, and road surfacing is of concern. As the road surface becomes rougher, the noise level generated by all vehicles increases (Cannelli et al., 1983). The correction $\Delta L_{10} = 4 - 0.03p$, where p is the percentage of heavy vehicles, from Equation 4-2, suggests that the noise increase due to rough road surfacing decreases as the number of heavy vehicles in the flow increases. No explanation for this relationship is given by the authors.

4.1.5 Interaction Between Noise Generation Variables

It should be noted that the effects of the three traffic noise generation variables flow rate, average speed, and composition of the traffic stream are all interrelated. Firstly, the type of flow can determine whether or not a relationship between the noise level and speed can be found. At low speeds, in interrupted flow conditions, speed is unlikely to be as significant a factor, as discussed above. Secondly, an increase in the number of heavy trucks in the flow, while increasing the noise level, can also reduce the average speed of traffic, which results in lower noise levels. Thirdly, the flow can increase to a point near capacity at which the average speed decreases. The decrease in noise due to this decrease in speed may offset the increase in noise due to the high flow rate. The last two examples of interaction between the three basic variables are discussed below in more detail.

It would naturally be expected that the greater the number of heavy trucks in the flow, the higher the noise level would be. However, in reality, an increase in the percentage of heavy vehicles in the vehicle stream can lower the average speed of traffic. This in turn lowers the traffic noise level. Model 1 accounts for the relationship between speed and the percentage of heavy trucks in the traffic stream. In general, the noise level varies with the logarithm of speed. However, the extent to which it varies depends on the number of heavy trucks in the flow; if the percentage of trucks increases, the average speed will decrease. Thus, the more heavy trucks there are in the vehicle stream, the less the noise level will increase with average speed. Equation 4-2 is structured such that an increase in the speed term, V, results in a greater increase in the noise level when the percentage of heavy vehicles, p, approaches zero (Delany et al., 1976). The model still predicts that there would be an increase in the noise produced for traffic streams that have higher volumes of [illegible]lse being constant. This relationship also indicates that while all the models follow the simple additive nature shown in Equation 4-1 this formulation does not preclude the modelling of interactions between the variables.

Secondly, it should be noted that under certain circumstances an increase in flow may result in a decrease in noise level. If capacity is approached or exceeded, congestion may result. As congestion increases, the average speed may decrease which results in less noise produced. For example, a flow of 1800 vph with 2% heavy trucks could increase to 1900 vph with a corresponding decrease in speed from 70 km/h to 55 km/h (Gerlough and Huber, 1975). The noise level L_{10}, calculated using Equation 4-2, is 73.8 dB at a flow of 1800 vph and 72.5 dB at 1900 vph. The noise level decreases despite the increase in the flow rate. A confounding factor is that the noise produced by acceleration and deceleration in severely congested conditions increases the noise level because the noise associated with engine loading is higher than during free-flow conditions (Favre, 1987). Equation 4-9 includes a correction for traffic congestion. The rest of the models do not consider periods of congestion.

4.1.6 Noise Propagation Variables

There are also factors introduced in the models that influence the propagation of the noise after it has been generated at the source. These factors and the models to which they apply are shown in Table 4-5.

Table 4-5.Traffic Noise Propagation Factors

Range and Sound Level	Model	Distance From Source	Ground Cover	Barriers	Angle of View	Reflection by Facades	Road Width
High Speed L_{eq}	Model 2	Y					
	Model 3	Y	Y	Y	Y	Y	
	Model 4	Y	Y	Y	Y	Y	
	Model 5	Y				Y	
High Speed L_{10}	Model 1	Y	Y	Y	Y	Y	
	Model 6	Y				Y	
Low Speed L_{eq}	Model 8	Y				Y	
	Model 9	Y				Y	
Low Speed L_{10}	Model 7	Y	Y			Y	Y
	Model 10	Y				Y	

As would be expected the traffic noise decreases as the distance between the receiver and the source increases. Different ground cover such as shrubbery, grass or snow can absorb sound in different ways. If sound easily penetrates the ground cover, as in the case of thick grasses, more sound will be absorbed than if the ground is impenetrable, as in the case of asphalt (Delany et al., 1976). Absorption of sound by the air itself is only significant at distances greater than 300 m from the source (Favre, 1987).

The presence of building facades complicates the prediction of noise levels because facades cause multiple reflections, scattering and diffraction of sound waves (Favre, 1987). Among other properties, the smoothness of facades can reduce the amount of noise that is absorbed by the facade (Radwan and Oldham, 1987). The height of the receiver can determine whether or not the height of the buildings are a concern. Gaps between buildings can significantly reduce the noise level heard near the street. Models 2, 5, 6, 7, 8, 9 and 10 are limited in their ability to help examine these and other effects. It should be noted that Model 2 was created in part to evaluate the accuracy of prediction models lacking all but the most basic factors.

Noise barriers or screens are the primary means of mitigating traffic noise. Sound energy can be diffracted over the top or around the edges of a barrier (Favre, 1987). The noise reduction provided by a barrier depends on the height of the source and receiver, the distance separating them, and the geometry of the barrier. Models 1, 3 and 4 are detailed in their evaluation of the insertion of a barrier; these models were developed in part to evaluate the effectiveness of noise barriers.

Model 1 predicts noise propagation in the greatest detail. The corrections in the model present a summary of how these propagation factors affect the noise level calculated in the basic formula (Delany et al., 1976).

4.1.7 Summary of Noise Prediction Models

This section provided an overview of traffic noise prediction and identified the influence of different parameters on noise levels. Ten empirical traffic noise prediction models were introduced. The models have similar mathematical approaches to estimating noise levels. There were shown to be two different prediction regions, one characterized by interrupted flow and speeds below 50-60 km/h and the other by free flow and speeds above 50-60 km/h. All of the models take into account the influence of traffic volume and composition on generated noise levels. Those models specifically designed for the interrupted flow regime do not include speed as a factor influencing noise generation, but those designed for the free flow regime do. Models 1 and 8 also include the effect of road surfacing and gradient on noise generation. It has also been noted that the models use different breakdowns of traffic composition, and that their equations reflect differences in the contributions of specific vehicle types to noise levels. The ten models vary in their treatment of the propagation of noise in the prediction of noise levels. Although all ten models include a term for the distance between the line source and the receiver, Models 1, 3 and 4 permit the most use of detail regarding the factors affecting noise propagation.

The number of heavy vehicles in the traffic stream is a basic variable used in all of the models. While most of the models differentiate between different vehicle classes there is no standard methodology for doing so. The average speed is only an influence in free flow conditions which are modeled by Models 1 through 6. Model 8, designed for prediction of noise in interrupted flow conditions, includes a correction factor which is used for to approximate the noise level at higher speeds. The road surfacing/tire interface is a factor that only becomes important at high speeds and is only included in Models 1 and 8. The effect of gradient and the proximity to a junction is a function of engine loading -- the gradient is included in Models 1 and 8 and the proximity to a junction is included in Models 5, 6, 8, 9 and 10. Because the purpose of this chapter is to assess measures of responsibility based on the noise generated by different vehicle classes, the parameters identified in Table 4-3 will form the basis for further analysis in this chapter.

4.2 Equivalency Factors -- Noise (EF_N)

An equivalency factor, as defined in this thesis, is a numerical value that identifies the relative contribution of different vehicle classes in a given traffic stream to some physical measure. It will be shown later that this measure of relative responsibility can be used to allocate the costs associated with noise generation to different vehicle classes.

Almost all equivalency factors in engineering are calculated with respect to some base condition. As an example, Load Equivalency Factors (LEFs) relate relative pavement damage to axle type and weight and are derived with respect to an 18 KN single axle load (Rilett, Hutchinson and Haas, 19?8). In this chapter the base to which the EF_N is calculated is the average noise generated by a standard automobile under prevailing conditions. It should be noted that this implies that all automobiles produce an equivalent amount of noise regardless of type. It is not felt that this is a limiting assumption because the vast majority of traffic noise models of line sources do not distinguish between different automobile types.

The calculation of an EF_N involves identifying the noise generation of each of the vehicle classes for the stated operating conditions. The marginal contribution of all vehicle classes to the traffic noise has to be identified and it is this contribution, or rather the relationship of this contribution to the contribution of the base vehicle class, that defines the EF_N. In essence, the EF_N relates the number of additional automobiles that would be required to produce to the same amount of noise as one additional vehicle of the different vehicle class, all else remaining equal. The EF_N may be derived by solving the following equality:

$$\frac{dL_X}{dVC_i} = EF\_N_{i-A} \frac{dL_X}{dVC_A} \qquad [2]$$

where:

L_X	Sound level (x = eq, 10, 50, 90, etc.)
EF_N_{VC-A}	Equivalency Factor for Noise for given vehicle class i to automobile A
VC_i	Volume of vehicle class i
VC_A	Volume of automobiles

For example, in the case of the UK DoE Model, Model 1, the following equality was solved to determine the EF_N:

4.2.1 EF_N's from Noise Prediction Models

The EF_N's for the noise prediction models shown in Table 4-2 were calculated and the results are tabulated in Table 4-6. It is important to note a number of key points underlying Table 4-6. The first is that the EF_N's were calculated for all vehicle class types in the respective models. As discussed previously the vehicle classes include both automobiles and heavy trucks with some models also examining medium trucks. As well, the flow was assumed fixed at 1,000 veh/h and the total percentage of heavy trucks and medium trucks was 10 percent. This latter assumption was necessary in order to identify a numerical value of the EF_N. Note that the values of the other variables were not assumed because the calculated EF_N's are independent of them. It was assumed in Table 4-6 that the speed in the interrupted flow - low speed models was 40 km/h, and the speed for the uninterrupted flow - high speed models was 80 km/h. In summary, the EF_N values in Table 4-6 are a function of some combination of speed, vehicle flow, vehicle class and percentage of heavy trucks depending on which model was used to calculate them. The sensitivity of the values shown in Table 4-6 to these variables will be examined later in this section.

Table 4-6. Sample EF_N's

Range and Sound Level	Model		EF_N (heavy : light)	EF_N (medium : light)
High Speed, L_{eq}	Model 2		15	10
	Model 3	3a	33.18	12.04
		3b	66.19	15.15
		3c	11.88	6.43
		3d	11.66	5.48
	Model 4	also 3e	20.59	8.37
	Model 5		6.10	
High Speed, L_{10}	Model 1		7.25	
	Model 6		6.72	
Low Speed, L_{eq}	Model 8		8	
	Model 9		10	6
Low Speed, L_{10}	Model 7		13	9
	Model 10		10	6

There are a number of key points that can be identified in Table 4-6. The first is that the EF_N for heavy trucks ranges from a low of approximately 6 to a high of approximately 66 for the stated conditions. This indicates that there could be an elevenfold difference in the predicted number of automobiles that would be equivalent to a heavy truck depending on which model is used. It should be pointed out that the STAMINA model, which is used by many transportation jurisdictions in North America, gives by far the highest EF_N values. In addition, models 3c and 3d give approximately the same results. This is a direct result of the fact that both models were calibrated using the same data set. As would be expected the EF_N for heavy trucks is higher than that for medium trucks for all of the models.

4.2.2 Sensitivity Analysis of EF_N to Speed

Figure 4-1 shows the relationship between EF_N and speed for the uninterrupted flow- high speed models.

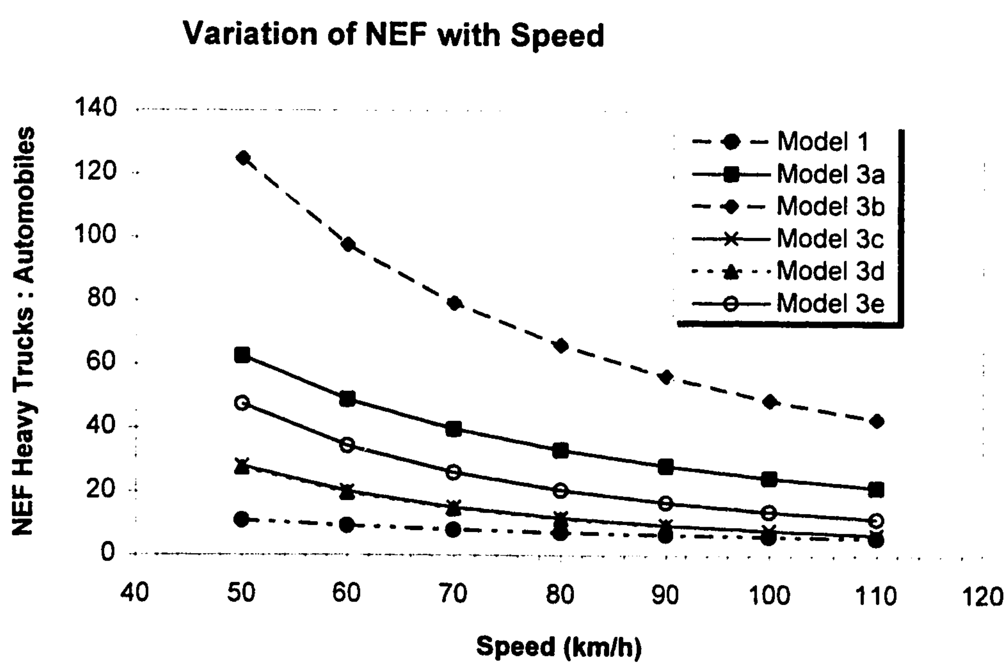

Figure 4-1. EF_N versus Speed

Note that the EF_Ns do not vary with speed in any of the interrupted flow models and consequently are not displayed in Figure 4-1. Of the high speed regime models, only Models 1, 3 and 4 have EF_Ns that varied with speed and it may be seen that for these latter models the EF_N decreases at a decreasing rate with speed as shown in Figure 4-1. As would be expected the curves from the five calibrations of Models 3 all followed similar trends with the difference in absolute values reflecting the different calibration parameters. The EF_N derived from Model 1 also decreases with speed although at a much smaller rate.

From a theoretical point of view the relationships identified above would be expected. In low speed traffic, engine and exhaust noise dominates over that produced by other traffic noise generation sources. In addition, the engine and exhaust noise associated with trucks is much louder than that of automobiles. The difference in the contribution of sound to the overall noise level between trucks and cars is large at low speeds, indicating that the EF_N value would be higher at lower speeds all things being equal.

It has also been found that there is no direct relationship between speed and noise generation for all vehicle types when speeds are below 50-60 km/h due to different rates of acceleration and gear selections by different drivers (Jones and Hothersall, 1980). This fact would explain why there was no EF_N - speed relationship found for the low speed regime models.

The noise produced by tires on the road surface, however, is similar in automobiles and trucks. At higher speeds two important phenomena occur: 1) tire noise begins to dominate the noise generation, and 2) heavy vehicles operate in higher gears with little shifting. These two effects result in the fact that the relative noise generation levels between automobiles and trucks will be closer as speed increases all other things being equal. As an example, it has been found that at lower speeds heavy trucks are up to 17 dB(A) louder than automobiles, and at high speeds heavy trucks are only up to 9 dB(A) louder (Buna, 1987). The end result is that at higher speeds heavy trucks will have a lower EF_N all else being equal. Of course, the magnitude of the noise generated will increase with speed as discussed earlier.

4.2.3 Sensitivity Analysis of EF_N to the Percentage of Heavy Trucks

Of all the models examined only the EF_N values based on Models 5 and 6 varied with percentage of heavy trucks. Figure 4-2 shows the relationship between the EF_N and percentage of heavy vehicles for these models when the traffic flow is 1,000 veh/h and the speed is 80 km/h. It can be seen that as the truck percentage approaches 20 the EF_N based on the L_{eq} model increases approximately 2.2 times while that based on the L_{10} value approximately triples.

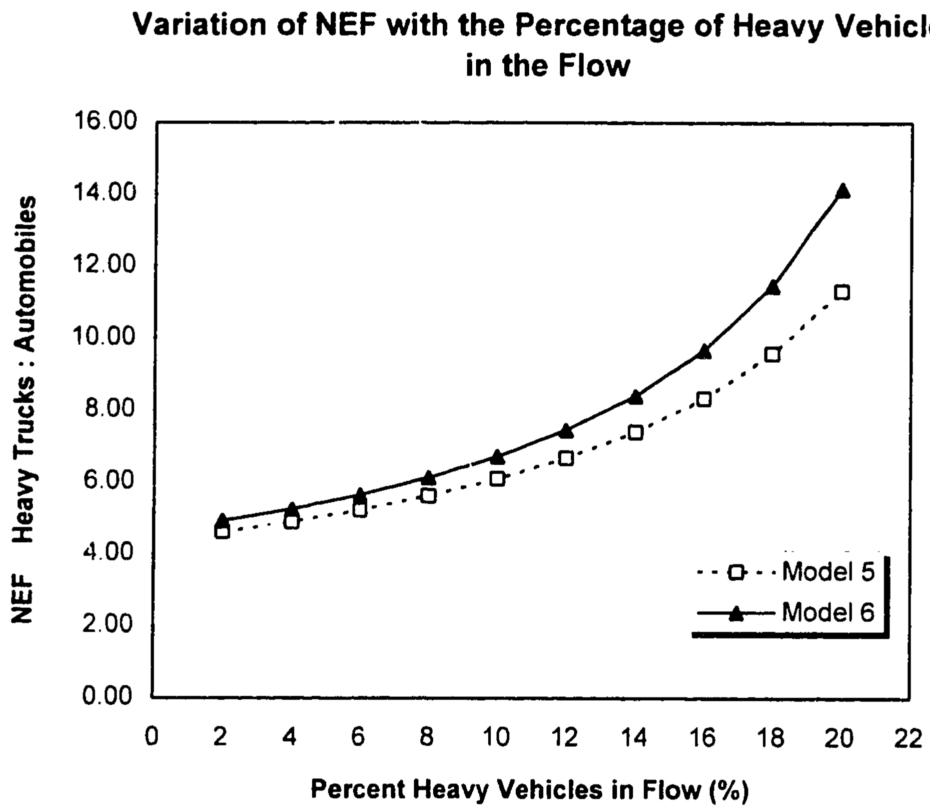

Figure 4-2. EF_N versus Percentage of Heavy Vehicles

Putting this relationship into words, the more heavy trucks there are relative to automobiles in the vehicle stream, the greater an individual truck's contribution is to the overall noise level. Consequently, the average truck is modeled as having an increase in the noise generation and/or propagation when a truck is added at the margin. This behavior of Models 5 and 6 is explained by the logarithmic increase in the noise levels L_{eq} and L_{10} with an increase in the percentage of heavy vehicles. The discontinuity in the traffic stream due to the presence of a heavy truck in lieu of an automobile increases the noise generation and this increase is directly related to the percentage of heavy trucks. In summary, not only are trucks louder but as their percentage increases they have an interaction affect, possibly due to increased maneuvering, that increases the amount of noise generated.

4.2.4 Sensitivity Analysis of EF_N to Other Parameters

By definition the EF_N should only change when the difference in noise generation between trucks and automobiles changes. Although only traffic speed and the percentage of heavy trucks were identified in the preceding sections as factors that affect the EF_N, it is possible to hypothesize that other parameters could have an effect on EF_N as well.

For example the EF_N would be expected to increase with increasing gradient because the increased noise related to the increase in engine loading and gear shifting would be more significant in trucks than in automobiles. Similarly, the closer the estimation point is to an intersection, the more acceleration/deceleration maneuvers would take place due to changes in the flow of traffic. The resulting engine and exhaust noise would increase the difference in noise generation between trucks and automobiles compared to freer flowing conditions, resulting in a higher EF_N. The final factor that may be related to the EF_N is road surfacing. It has been shown that tire loading and tread patterns can affect the noise level by as much as 6 dB(A) (Tyler, 1987).

It should be pointed out that no relationships between the EF_N and gradient, proximity to junctions, or road surfacing could be found in any of the models considered in this section. These factors are assumed to have no explicit interaction affects. That is, it is assumed that the above factors have the same impact on noise regardless of the vehicle type. Nevertheless, this assumption is appropriate given the limited data and the fact that the models are used at a fairly aggregate level. For example, of all the noise prediction models studied only Model 1 represents an attempt to develop interaction terms between flow, speed and percent of heavy trucks. In other models, the aggregate effect on the noise level of this interaction may be accounted for in the coefficients of the separate parameters, but the interaction itself is not examined in any detail.

4.2.5 Application of EF_N's in Transportation Engineering

There are two basic reasons that EF_N's may be considered important. The first, and most obvious is that the relative responsibility of noise generation by different vehicle classes may be quantified. They may then be used in analyzing policy design decisions involving the different vehicle types. As an example, the EF_N's may be used to explicitly show the trade-off between increased truck volumes by truck type on community noise levels.

The second reason is that the EF_N's can serve as a basis for allocating costs of noise attenuation directly to those vehicles responsible for the noise. As discussed in Chapter 3, the allocation of these costs to different road users can follow several different principles. Allocation might depend on users' ability to pay, on the proportion of driving benefits that are received by users, or on the proportion of the costs for which users are responsible (Wong and Markow, 1984). Traditionally, pavement costs have been allocated on the basis of the latter and is also known in the literature as the occasioned cost concept. If users are to be charged for noise on a similar basis, then a responsibility measure for each vehicle class has to be identified. It is proposed that the EF_N is an acceptable measure of responsibility for noise pollution. The following section will provide an example of how these EF_N values may be used in the cost allocation process.

4.3 Sample Problem

Consider an urban arterial roadway with 4 lanes, at-grade intersections, and an average traffic speed of 40 km/h. The geometrics subsequently change into a six lane divided highway with an average speed of 80 km/h. The four lane road serves a residential community that borders both sections of the road. To alleviate the high noise levels in the community, the construction of a series of noise barriers along both sections of the road is proposed. In this example it is assumed that the costs associated with construction of the barrier will be collected from the users of the roadway using electronic toll collection technology.

The noise barrier is to be made out of reinforced concrete with an absorptive coating. The cost of materials and installation for the barrier is US$1, 000 per linear meter. If the length of the barrier is 1 km and is placed on both sides of the roadway the capital cost would be 2 million dollars. Assuming a 20 year analysis period and a discount rate of 4% the associated capital recovery factor is 0.0736 which would result in an average annual cost of US$147,164. For comparison purposes it is assumed that a 1 km barrier will be constructed on both the arterial and highway sections of the roadway.

According to the proposal, the toll rate for each vehicle class will be determined on the basis of the occasioned cost principle. In accordance with this principle, each vehicle will be charged in direct proportion to the costs it occasions, or in other words, the noise it produces. In the section of concern the peak period hourly flow is 5,000 veh/h (both a.m. and p.m.) and the community noise ordinance is broken 260 days of the year during the peak period of flows. Thus, a total of 260,000 vehicles per year are deemed responsible for the construction of the barrier. Of those vehicles, 90% are automobiles and 10% are heavy trucks. For simplicity it is assumed that the traffic is not increasing although traffic growth may be easily handled using standard discounting techniques (Rilett, 1988).

The equivalency factors that were calculated in Section 4.2 will be used to assign the responsibility measures to the vehicles on the highway. For demonstration purposes Models 7 and 9 will be used for cost allocation on the low speed, interrupted flow arterial section, while Model 3 has been selected to allocate costs on the uninterrupted flow, high speed highway section. These models were selected only for the purposes of demonstration and a sensitivity analysis of these values will be performed in the following sections.

4.3.1 Cost Allocation Procedure

The first step in the cost allocation procedure is to identify the total number of automobile equivalents. The total number of auto equivalents is determined by multiplying the number of vehicles in each class by the EF_N of that class as shown in Equation 4-12.

[4-12] $$AE = \sum_{i=1}^{n} (VC_i)(EF\_N_{i-A})$$

where

AE	Number of Equivalent Automobiles
EF_N_{i-A}	Equivalency Factor for Noise for given vehicle class i to automobile vehicle class A
VC_i	Volume of vehicle class i

For demonstration purposes the highway section using the EF_N from Model 3a will be used as an example and the assumed speed will be 80 km/hr. The EF_N can be determined using Equation 4-4 as follows:

Assuming: 4500 automobiles, 500 heavy trucks, 80 km/h average speed

REMELS: for autos $38.1 \log(80) - 2.4 = 70.1077$

for trucks $24.6 \log(80) + 38.5 = 85.3160$

Add Flow Corrections:

$L_{eq\ auto} = 70.1077 + 10 \log(4500 \times 15/80) - 25 = 74.3699$

$L_{eq\ truck} = 85.3160 + 10 \log(500 \times 15/80) - 25 = 80.0357$

$L_{eq\ +\ x\ autos} = 70.1077 + 10 \log(4500+x) \times 15/80) - 25$

$L_{eq\ +\ 1\ truck} = 85.3160 + 10 \log((500+1) \times 15/80) - 25$

SOLVE: L_{eq} (1 truck added) = L_{eq} (x autos added)

$$10 \log (10^{74.3699/10} + 10^{L_{eq\ +\ 1\ truck}/10})$$

$$= 10 \log (10^{L_{eq\ +\ x\ autos}/10} + 10^{80.0357/10})$$

x is found to be 33.18. This is the Model 3a EF_N for a speed of 80 km/h.

Using this EF_N and Equation 4-12, the 260,000 vehicles/year translates into 5,720,000 automobile equivalents.

The second step is to identify the average cost per automobile equivalent by dividing the total cost of the noise barriers by the total number of auto equivalents as shown in Equation 4-13. Given that the total cost is US$147,164 this results in an average cost per auto equivalent of 2.57 cents.

[4-13] $$C_{AE} = \frac{TC}{AE}(EF\_N_{i-A})$$

where:

TC	Total Cost
AE	Number of Equivalent Automobiles
EF_N_{i-A}	Equivalency Factor for Noise for given vehicle class i to automobile vehicle class A
C_{AE}	Cost per automobile equivalent

Lastly the cost per vehicle class is arrived at by multiplying the average cost per vehicle equivalent by EF_N of the vehicle class in question as shown in Equation 4-14. For the example this results in an average cost of 2.57 cents/ km for automobiles and 33.45 cents/km for heavy trucks.

[4-14] $$C_i = (C_{AE})(EF\_N_{i-A})$$

C_{AE}	Cost per automobile equivalent
EF_N_{i-A}	Equivalency Factor for Noise for given vehicle class i to automobile vehicle class A

4.3.2 Cost Allocation Results

The costs allocated to an individual vehicle making a single trip through the arterial section are shown in Figure 4-3.

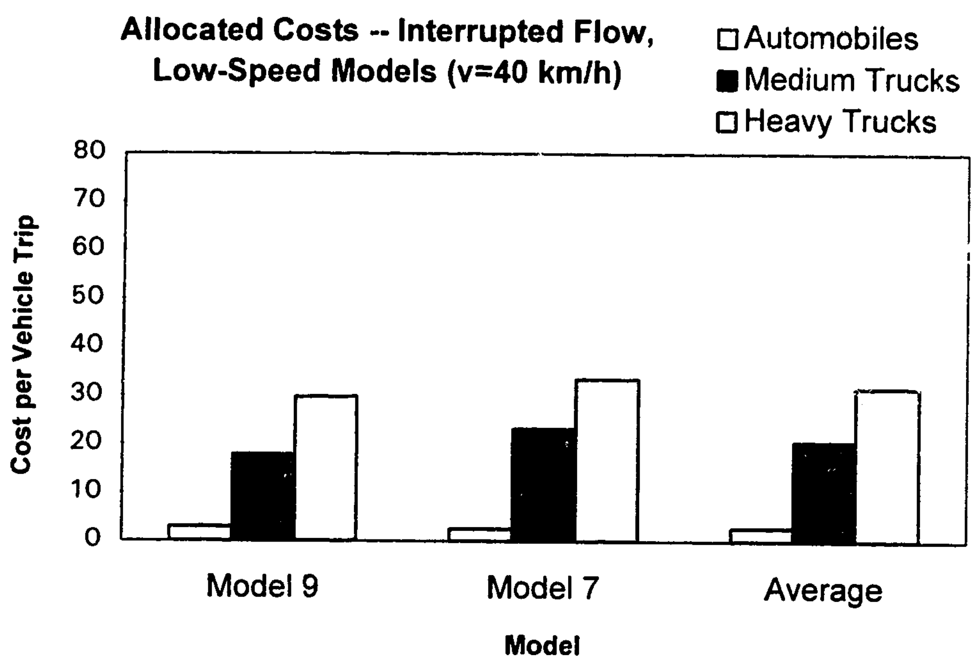

Figure 4-3. Allocation of Costs: Low Speed Models

It may be seen that automobiles would pay 2.8 cents per trip based on the characteristics of the travel on the arterial section using the average of the two low speed regime models. Based on the average of Models 7 and 9, medium trucks would pay an average of 20.5 cents, and heavy trucks would pay approximately 31.6 cents.

These values reflect the responsibility of each vehicle class for the noise levels in the corridor and the costs of abatement, which are assumed, in this example, to be the only true costs of the noise intrusion on the community.

The costs allocated to individual vehicles making a single trip through the highway section are shown in Figure 4-4.

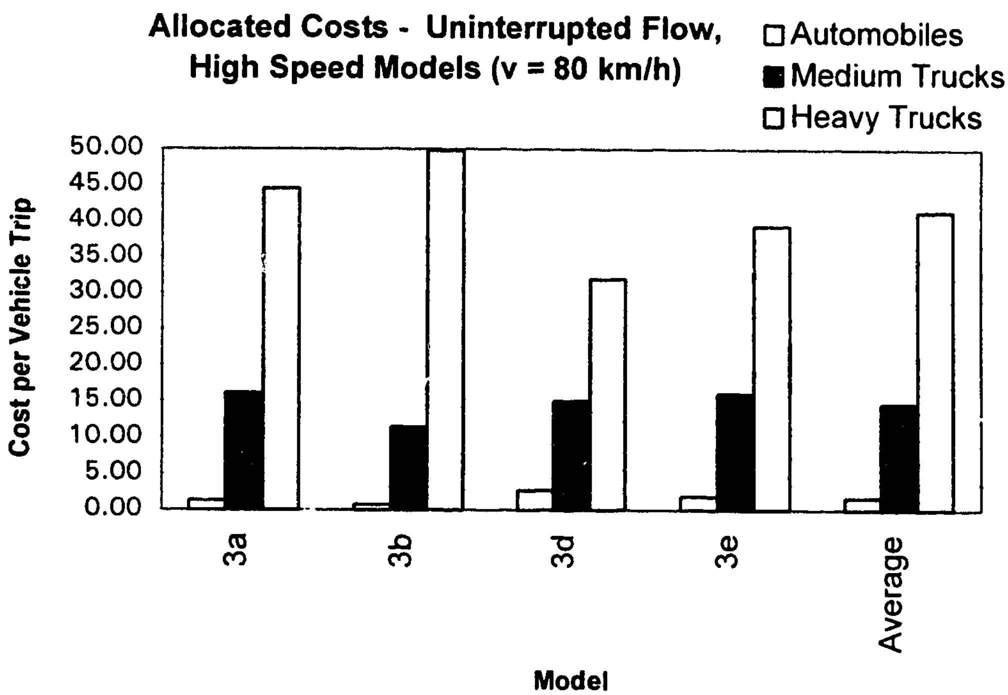

Figure 4-4. Allocation of Costs: High Speed Models

It is shown that automobiles would pay an average of 1.7 cents; this is calculated using the results of the high-speed uninterrupted flow models. Medium trucks would pay 14.7 cents and heavy trucks would pay 41.4 cents. Heavy trucks still pay significantly more than automobiles when costs are allocated based on the highway section. Figure 4-4 illustrates the importance of choosing a representative noise prediction model to allocate costs in this manner. The models calibrated for use in Florida, 3c (Dunn and Smart, 1986) and 3d (Wayson et al., 1993), yield tolls for heavy trucks of approximately 32 cents. The models calibrated earlier using FHWA data, 3a (Barry and Reagan, 1978) and 3b (Rickley et al., 1978), yield values for heavy trucks of 45 cents and 50 cents, respectively.

The choice of models used in this example is important. It was discussed earlier that EF_N's should decrease as speed increases, because the difference in noise generated by trucks relative to automobiles decreases as speed increases. This relationship can be demonstrated using a single model, but cannot necessarily be proven between different models. It is interesting that in this example, because EF_N's derived from Models 3 and 4 are relatively high, truck operators actually pay proportionately more at high speeds than they would at low speeds. Models 7 and 9 yield tolls for heavy trucks of 30 cents and 33 cents, respectively. The lowest heavy vehicle EF_Ns from the STAMINA models are derived from Models 3c and 3d; the tolls derived from these models are both equal to 32 cents. The low speed and high speed EF_N's should be chosen to reflect the true behavior of this function between interrupted-flow and free-flow regions.

4.3.3 Sensitivity Analysis

Figure 4-5 shows the relationship between the percentage of heavy trucks and the allocated costs to automobiles and heavy trucks for the two scenarios. As would be expected as the number of heavy trucks decreases the cost per truck decreases because there are more vehicles to allocate the costs to. In addition, the decrease is at a decreasing rate as evidenced by the convex function. This relationship holds true for both the highway and arterial scenarios.

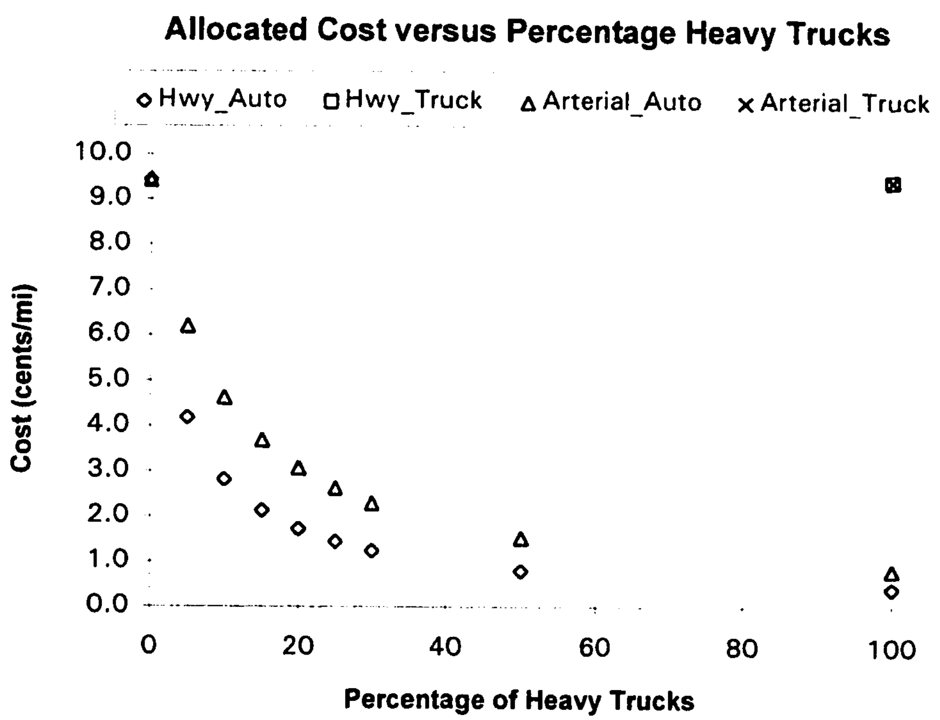

Figure 4-5. Allocated Cost Versus Percentage of Heavy Trucks

Figure 4-6 illustrates the relationship between the peak hour volume used in the question and the allocated costs with 5,000 veh/hr representing the base situation. It may be seen that as the vehicles increase the cost per truck decreases at a decreasing rate. Similar to the previous sensitivity analysis the effect may be attributed to the greater number of heavy vehicles to spread the cost too. Note that in both sensitivity analyses it was assumed that the aspects of the roadway was such that the volume could be adequately handled for the given speed.

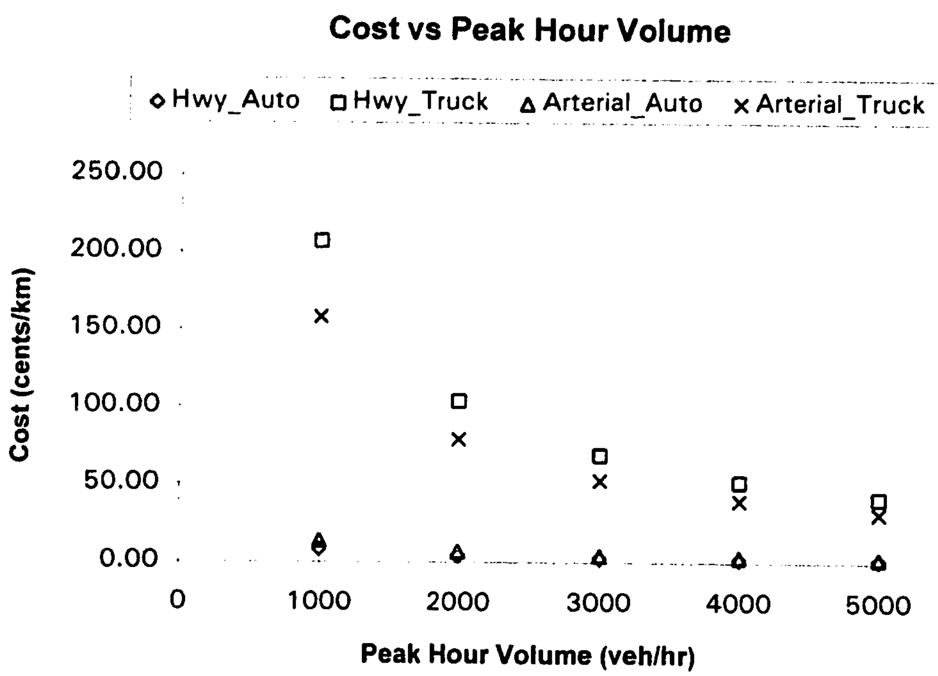

Figure 4-6. Allocated Cost Versus Peak Hour Volume

While it was not the intent of the chapter to examine the effects that this type of pricing scheme would have on the demand an opportunity presents itself to hypothesize about the effects of such a pricing scheme. For example, the toll charges in one corridor may force truck operators to use alternative routes. The charge to automobile drivers of five cents per trip is likely too low to result in any route changes although for extended lengths it may have an effect. However, shippers and other heavy vehicle operators would obviously be affected by the 50 cent charge allocated to heavy vehicles. Operators might choose an alternative time of day for their trips. In the longer term, modifications might be made to vehicles, and designs might be improved to reduce the noise generated by diesel trucks.

The noise charging scheme would also have impacts on development. Once it is seen that funds are readily available for noise abatement, demand for barriers, sunken highways, and other noise attenuation would likely increase. In addition, the cost of constructing a new roadway would effectively be reduced if motor vehicle operators were to pay for noise abatement through tolls. The money used to construct sound barriers today is obtained from road users and non-users in the form of taxes. In the electronic tolling scheme, money for noise barriers would be taken from users according to their responsibility for noise instead of according to the structure of taxation. This changes the distribution of income in the community, which has historically been very important to society. Albeit a small change, the income effects of noise charges would contribute to the aggregate effect of similar projects and user charges.

4.4 Concluding Remarks

Several important points should be drawn from this chapter. Analysis of different noise prediction models shows that EF_N's are not completely independent. The EF_N for heavy trucks was shown to decrease with increasing speed in the free-flow region. It was also shown that EF_N's are higher in the region of free-flow at high speeds than in the region of interrupted flow at low speeds. It was determined that because of gear changes and different driver behavior, there is no direct relationship between the EF_N and speed in the interrupted flow low-speed region. It was hypothesized that the other factors influencing the generation of noise, including road surfacing and tire tread, road gradient and proximity to an intersection also affect the EF_N.

In addition, new concerns arise from this discussion. It is important to distinguish between different definitions of heavy trucks, medium trucks and automobiles before closely comparing EF_N's. Shifting the weight classification boundary between medium trucks and heavy trucks has great implications when the medium and heavy truck EF_N's differ by as much as 51, as they do in the STAMINA model 3b, shown in Table 3-6. As well. certain accommodations must be made for variation within the classes of vehicles themselves. A poorly maintained car with a loud exhaust system being driven aggressively may bear as much responsibility for high noise levels as a properly maintained heavy truck. To be used practically, EF_N's should reflect such variation. Finally, EF_N's may be used as a model for examining air quality concerns; emission equivalency factors derived from models of vehicular emissions should prove useful in showing which vehicles are responsible for the costs of traffic pollution.

Chapter 5

Measures of Responsibility for Air Pollution

5.0 Introduction

The purpose of this chapter is to derive and analyze equivalency factors for air pollutants. This chapter is broken up into three sections. Section 5.1 includes an investigation of the parameters affecting vehicle emissions, as well as a description of the most widely used emission model in North America, the MOBILE model. Section 5.2 details the calculation of equivalency factors for HC, CO and NO_x pollutants from the MOBILE model. In Section 5.3, the EF_p's derived in Section 5.2 are used to calculate emission charges for a hypothetical scenario.

For a variety of reasons, a mix of SI units and US (Imperial) units is used throughout this chapter. The air quality models upon which the analysis is based are designed and calibrated using US units. Many increments and variables used in the models are defined in US units. The most common measure of air pollution emission rates is actually a mix of SI and US units, grams per mile. Furthermore, the bulk of air quality research is performed in US units. US unit definitions and conversions are provided in the glossary in Appendix A.

5.1 Emission Models and Factors Influencing Emissions

5.1.1 Fuel Factors

Parameters affecting the rate of emission of pollutants from fuel include the type of fuel, the oxygen content, the volatility, the sulfur content, the benzene content, the aromatic hydrocarbon content, and the lead and heavy metals content (Guensler, 1994).

Fuels commonly used by motor vehicles today are gasoline, diesel fuel, propane, natural gas, and methanol. The combustion of diesel fuel results in lower HC, CO, NO_x and CO_2 than the combustion of diesel fuel. However, the high sulfur content of diesel fuel and the high amount of particulate matter emitted by diesel engines may make the combustion of diesel fuel a greater health risk (SAE, 1994). Ten times as many respirable particulates are emitted by diesel engines than gasoline engines on a per-mile basis (Krupnick, 1991).

The lower the volatility of the fuel, the fewer the evaporative emissions. For example, diesel fuel has a lower volatility than gasoline, and therefore results in lower diurnal, running, and hot soak evaporative emissions (Hassounah and Miller, 1994). The MOBILE emission model, described later in this section, includes a correction to its base emission factors for fuel volatility, which applies to HC and CO emissions from vehicles between the years 1971 and 1979 (Cottrell, 1992).

5.1.2 Vehicle Design Factors

In general, vehicles can be separated into two groups: low emitters and high emitters (Washington, 1994). High emitters might be classified, for example, as vehicles that produce ten times as much CO pollution as low emitters. A vehicle may be classified as a high emitter if its emission control equipment fails. This may have as much to do with design as with vehicle's age. Older vehicles are worse emitters than newer vehicles, for two reasons (Fieber et al., 1992). First, certain older vehicles were designed under looser emissions restrictions. As an example, vehicles built before the mid to late 1970's were built without catalytic converters. Catalytic converters are made of a mixture of metals on a ceramic base mounted in the exhaust line of a vehicle. The metals catalyze the reaction that creates CO_2 and water (H2O) from CO and HC, thereby reducing HC and CO emissions (Hassounah and Miller, 1994). As well, most vehicles built in the late 1980's and 1990's have onboard computers that adjust the fuel to air ratio to optimize the combustion of fuel, resulting in fewer products of incomplete combustion. Second, older vehicles tend to be poorly maintained, which results in higher levels of emissions and fuel consumption. The combination of age, design and poor maintenance results in the categorization of many older vehicles as high emitters.

Vehicles equipped with manual transmissions have higher HC emissions straight out of the engine than those equipped with automatic transmissions (Haskew and Liberty, 1992). However, both types of automobile conform to the same tailpipe emission standards, suggesting that the catalytic converters in vehicles with manual transmissions process larger amounts of HC (Haskew and Liberty, 1992).

5.1.3 Environmental Factors

The environment in which vehicles are being operated can also determine pollution levels. For instance, the temperature can determine the rate of formation of ozone. As well, since SO_2 is water soluble, the deposition of acids can be increased in rainfall. Cold weather can result in increased emissions of HC and CO because of incomplete combustion at cold engine temperatures and because catalytic converters do not function when they are cold (Hassounah and Miller, 1994). In hot weather, diurnal emissions can increase because more fuel evaporates at higher temperatures. Furthermore, HC, CO and NO_x emissions can all be expected to increase at higher altitudes, as shown in subsequent analysis in this chapter.

5.1.4 Vehicle Operation Factors

Emission Rates are largely determined by the operation of the vehicle. Some of these operating parameters are discussed below.

Starting

If the vehicle is started after a long period of inactivity, say, overnight, its emission rate will be higher than if it was started when it was still warm. This occurs simply because incomplete combustion takes place when the engine is cool, oil viscosity is high, and the catalytic converter does not function until it is hot. As well, vehicles with on-board computers operate in what is called open-loop condition before the engine is warmed up. Normally, an engine with an on-board computer operates in closed-loop condition, and the air flow and fuel to air ratio is adjusted by the computer. When an engine is warming up, it operates in open-loop conditions, with no modifications by the computer, and combustion is relatively inefficient (Guensler, 1994).

Speed

As average speed increases, the pollutant emission rates on a grams per second basis increase. However, because concentrations of pollution in urban areas are of particular concern, emissions are normally quantified on a grams per mile basis. Measured in grams emitted per mile, HC and CO emissions decrease by a factor of approximately five between 16 km/h (10 mph) and 80 km/h (50 mph). NO_x emissions decrease by a factor of two between 4 km/h (2.5 mph) and 32 km/h (20 mph) and then increase slightly up to 80 km/h (50 mph). The causal relationship between emissions and vehicle speeds will be examined during the development of a physical emission model at the University of California at Riverside and the University of Michigan (Barth, 1995). Many speed - emission profiles can be misleading if they detail the emissions of a composite vehicle rather than a particular vehicle type (Al-Deek et al., 1995). In other words, the speed-emission profiles used in emission prediction models are not always representative of the profile of an individual vehicle. A measure of responsibility that is based on the emissions of a composite vehicle will not necessarily reflect the true relationship between emissions and speed for any particular vehicle.

Acceleration

HC, CO and CO_2 emission rates are higher when vehicles are accelerating and, sometimes, when vehicles are decelerating (Hassounah and Miller, 1994). Acceleration causes enrichment of the fuel to air ratio. Enrichment is needed to provide instantaneous engine power. It also controls the cylinder detonation and protects engine parts from very high combustion temperatures (Guensler, 1994). When the fuel to air ratio in the cylinders of an engine is increased, CO and HC emissions increase substantially. An emission analysis by the California Air Resources Board (CARB) found that a single hard acceleration of 9.6 km/h per second (6 mph per second) could increase the total emissions for a trip by a factor of 2 (Drachand, 1991). To demonstrate the complexity of emissions behavior in traffic conditions, consider that although smoothing traffic flow to relieve congestion would lower HC and CO emissions, NO_x emissions would theoretically rise (Cottrell, 1992).

Deceleration

Strong deceleration can also cause enrichment and, thus, increase HC and CO emissions (Guensler, 1994). Both acceleration and deceleration may also affect the rate at which fuel is returned to the gas tank from the injectors. This can increase the temperature of the fuel in the tank and result in increased evaporative emissions (Guensler, 1994).

Loading

The vehicle's payload or the gradient of the road can increase emission levels just as acceleration can by increasing the loads on the vehicle's engine. As an example of the importance of these engine loads, in instrumented vehicle tests with a Pontiac

Bonneville, CO emissions were found to increase by a factor of 2,500 and HC emissions were found to increase by a factor of 40 over normal operating conditions when moderate to heavy loads were placed on the car's engine (Kelly and Groblicki, 1993).

5.1.5 The MOBILE and EMFAC Models

It would be desirable to incorporate all of the factors influencing emissions into an emission model. However, the larger the area of study, the lower the level of detail incorporated into the model, and the more factors are forsaken.

There are two emission models widely used today: the MOBILE model developed by the EPA and the EMFAC model developed by CARB. In response to the findings of numerous studies, the Clean Air Act and the 1991 Clean Air Act Amendments were introduced by the federal government. As part of this broad legislation, all states are required to meet National Ambient Air Quality Standards (NAAQS) within a specific time (Stephenson and Dresser, 1994). The pollutants covered by the NAAQS are ozone, CO, particulate matter, lead, SO_2, and NO_2.

The US EPA MOBILE models, the California Air Resources Board EMFAC model, and the UK TRRL model are examples of speed factor models. The MOBILE 1 model was introduced in 1978. MOBILE 4.1 was released in 1991, and MOBILE 5A was released in 1995. A version known as MOBILE5C has been developed for Canada. EMFAC is a version of the MOBILE model developed for use in California, where vehicles must adhere to stricter emission standards. The

MOBILE model is widely used in North America and will be described in detail in this section.

5.1.6 Calculation of Emissions in MOBILE

As mentioned in the introduction of this chapter, the MOBILE model includes a mix of SI units and US units. US unit definitions and equivalencies with SI units are provided in the glossary in Appendix A.

The MOBILE and EMFAC models have basic emission rates for HC, CO and NO_x for eight vehicle classes. These vehicle classes are shown in Table 5-1.

Table 5-1. Vehicle Classes in the MOBILE Model

LDGV	Light-duty gasoline-fueled vehicles (passenger cars)
LDGT1	Light-duty gasoline-fueled trucks up to 6000 lbs. gross vehicle weight (light pickups and vans)
LDGT2	Light-duty gasoline-fueled trucks over 6000 lbs., and up to 8500 lbs.gross vehicle weight (heavier pick-up trucks and vans, and many commercial trucks)
HDGV	Heavy-duty gasoline-fueled vehicles over 8500 lbs. gross vehicle weight (heavier commercial trucks, including highway hauling trucks)
LDDV	Light-duty diesel-fueled vehicles (passenger cars)
LDDT	Light-duty diesel-fueled trucks up to 8500 lbs. gross vehicle weight (pickups, vans and many commercial trucks)
HDDV	Heavy-duty diesel-fueled vehicles over 8500 lbs. gross vehicle weight (heavier commercial trucks, including highway hauling trucks)
MC	Motorcycles

Basic emission rates and emission deterioration rates are available for each of these categories. The rates used in most cases are based on what is called the Federal Test Procedure, or FTP, a standard method of determining the emissions of given vehicles. In MOBILE, basic emission rates for a given year and fleet composition are multiplied by a number of correction factors, as outlined below:

Composite emission factor for given pollutant

= Basic emission factor (model, year) * fuel volatility correction (some years only) * composite correction factor * fraction of total travel contributed by model, year + refueling (HC) + running loss (HC) + crankcase and other evaporative (HC)

composite correction factor

= speed correction factor * extra loading factor * air conditioning factor * trailer towing factor * humidity factor

speed correction factor

= speed factor for model, year / cold start, hot start adjustment

speed factor for model, year

= constant (for year, speed, pollutant) / speed + constant *cold start, hot start adjustment*

$= 1 / [(w+x)/26 + (1-w-x)/16]$ where w = fraction of vehicles in hot-start mode

x = fraction of vehicles in cold-start mode

(Source: Cottrell, 1992)

This set of calculations is only used on LDGV, LDGT1 and LDGT2 vehicles newer than 1976. The range of speeds for which speed correction factors are available is between 2.5 and 65 mph. The same speed correction factors are used for speeds between 48 and 55 mph. The range of variables as corrections to basic emission rates in the EMFAC model covered by the California Air Resources Board is 0 - 65 mph speed, 0 - 105 F temperature, and 0 - 5 mph/sec acceleration (Cardlock, 1992).

The basic emission rates (BER) are determined through actual vehicle tests on an apparatus called a dynamometer, which consists of a large chassis with a roller under which the drive wheels of the vehicle are placed. The roller applies forces to the drive wheels to simulate the loading experienced in actual driving conditions. Vehicles are driven through cycles on the dynamometer that are designed to be indicative of driving patterns in urban areas. The driving cycle used in the FTP involves the following steps (Horowitz, 1982). A vehicle is placed on the chassis and emissions measuring equipment is attached. The engine is started when it is cold. The first 505 seconds after the engine is started is known as the cold transient stage.

Since the emissions are collected in fabric bags at the tailpipe of the vehicle, this stage is also referred to as the Bag 1 stage. The vehicle is then driven through the prescribed cycle. This is known as the hot stabilized or Bag 2 stage. The engine is then turned off, the vehicle is left for 10 minutes, the engine is restarted, and the vehicle is left idling for 505 seconds as in the first stage. This is known as the hot transient or Bag 3 stage.

The BER's are created by taking a weighted average of these test results, with 0.43, 1.00, and 0.57 being the coefficients applied to the Bag 1, Bag 2 and Bag 3 results respectively. This simulates a typical urban driving pattern where 43% of trips begin with cold starts and 57% begin with hot starts. Heavy duty vehicles, it should be noted, are tested on special engine dynamometers; the entire vehicle is not mounted on a chassis dynamometer. In Appendix C, the BER's are shown as they appear in the Block Data section of the MOBILE5a source code.

Figure 5-1 shows the linear slope of the BER equation for HC for a 1967 model year LDGV.

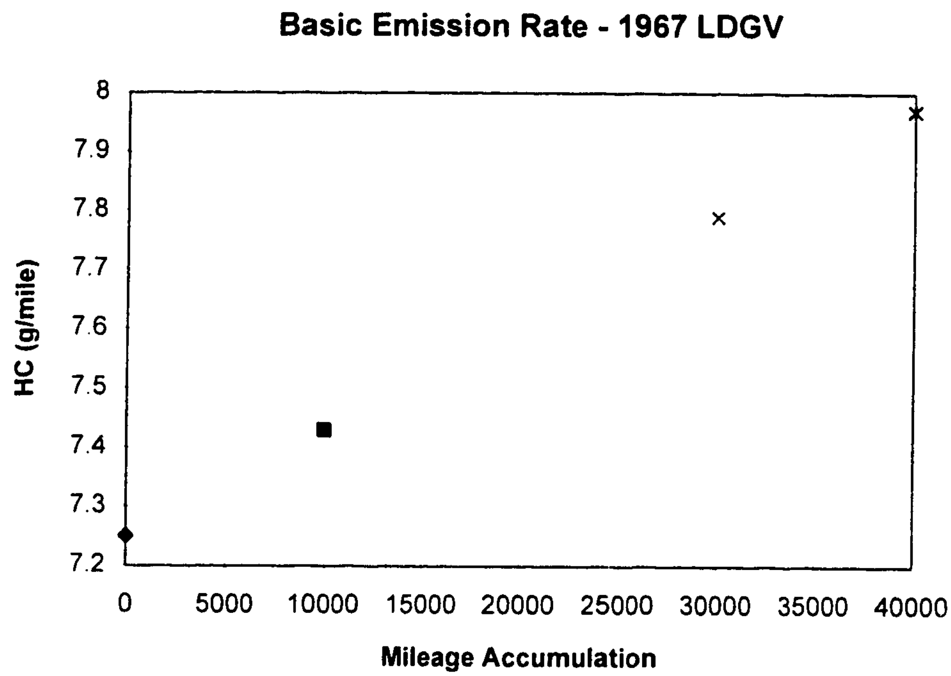

Figure 5-1. Basic Emission Rate Equation for 1967 LDGV

The 0-mile emission value is 7.25 grams per mile. The emission rate increases by 0.1[illegible] grams per mile for every 10,000 miles of accumulated mileage up to 40,000 miles. Similar BER curves are coded into MOBILE5a for CO and NO_x. Not shown is the steeper deterioration line for 50,000 miles and up, which is applied to most LDGV model years and LDGT1 and LDGT2 of model year 1991 and later. Because this deterioration curve is not applied over all vehicle classes and model years, it is left out of the analysis in the next section.

The average trip speed factor is increased to account for elevated rates of emissions. The elevated rate is treated as a discrete peak in EMFAC, while the average running emission rate is raised in MOBILE (Guensler, 1994). Various amounts of acceleration, deceleration, idling and cruising are incorporated into the speed correction factor (Cottrell, 1992). However, some operational activities, such as sharp accelerations and decelerations, which are responsible for disproportionate amounts of emissions, are not factored into the average speed (Guensler, 1994). Emission rates are specific to the driving cycle that is used in the test procedure.

5.1.7 Problems with MOBILE and EMFAC

Many problems have been identified with the two widely used models. The speed correction factor method yields uncertain results with high errors but no measure of uncertainty (Guensler, 1994). Sensitivity to variations in acceleration, deceleration, cruising and idling are not permitted with the models (Cottrell, 1992). It is now recognized by vehicle emission researchers that more attention must be paid to the accumulation of test data for high-emitting vehicles (Guensler, 1994). For example, even though they contributed 70% of total HC and CO in 1990, all vehicles built before 1981 have the same deterioration factor applied to their basic emission rates, while newer vehicles have individual deterioration rates (Fieber et al., 1992). Since these older vehicles are disproportionately responsible for emissions today (partly out of design and partly due to deterioration), the test samples from which data for these vehicles are drawn should be increased. It is also suggested that the treatment of HC evaporative emissions be given more attention, particularly in classes other than automobiles (Fieber et al., 1992). The representation of real-world driving behavior, instead of a generic driving cycle, will be the most difficult of these problems to reconcile.

This does not diminish the value of the analysis presented below. The MOBILE model can still be used to demonstrate the principle of occasioned cost equity in cost allocation. As well, the model reveals significant differences between different vehicle classes, model year groups, and mileage accumulations, as shown later in this chapter. Furthermore, the allocation of costs demonstrated here can be applied to modal emission models, described below, in the future to improve the equitable allocation of costs within vehicle classes.

5.1.8 Modal Emission Models

A new emission modelling approach is needed to make these estimations and to solve some of the deficiencies inherent in the MOBILE model. Two such models are under development today: One is being developed for the EPA by researchers at the Georgia Institute of Technology (Georgia Tech), and the other is being developed with National Cooperative Highway Research Program (NCHRP) funding at the University of California at Riverside (UC-Riverside). Significant supporting research is underway at the University of Michigan, Caltrans, and the California Air Resources Board (CARB).

A team at Georgia Tech is in the process of developing a modal emission model funded by the EPA. Their goal is to create a modal emission model within a Geographic Information Systems (GIS) framework that estimates emissions as a function of vehicle operating profiles. The model will likely be a stochastic model with emission factors for different vehicle operating modes. This requires a great deal of vehicle testing data; Georgia Tech has seven instrumented vehicles for model development.

A GIS-based working emission model will be tested in Atlanta, Georgia, early in 1996. This working model will be a research-level model, since a large amount of modal activity data will remain to be quantified. It is expected that a full modal emission modelling package will be available to municipal planning agencies in 1998.

UC-Riverside has been awarded a US$1.5 million contract by NCHRP to develop a modal emission model (Barth, 1995). The goal of the three-year project (NCHRP Project 25-11) is to develop a physical model based on second-by-second emissions and vehicle operation data. The different components of the model are the tractive power demand function, the engine power demand function, gear selection and engine speed, the emission control strategy and air/fuel ratio function, and a separate emission function which may simplify the model. The model will require accelerations, final and initial velocities, loads from road grades, and the use of air conditioning as vehicle operating parameters.

The project has three phases:

Phase 1 - Information gathering, model design, and development of new dynamometer testing protocol.

Phase 2 - Performing dynamometer emission tests on 300 cars making up a representative sample of the on-road fleet, development of the modal model, and validation of the model using an instrumented vehicle.

Phase 3 - Demonstrating how the model can be integrated with existing microscale (corridor, intersection) and macroscale (regional) transportation models. A system called the Integrated Transportation Emissions Model (ITEM) is a precursor to an integrated model and is being concurrently developed by the same team at UC-Riverside.

The group completed the first phase of literature and data collection in January 1996.

The University of Michigan has completed several modal emission projects. The Department of Physics is performing the testing and theoretical development of the models.

1. The group has been working for the past year on the theoretical development of a project funded by the Oak Ridge National Laboratory. The project goal was to measure second-by-second emissions from six vehicles to help improve the basis of modal emission models.

2. The group is also cooperating with researchers at UC-Riverside, assisting them with plans for recruiting and testing 300 vehicles and with the modelling of vehicles with malfunctioning emission controls for the NCHRP Modal Model.

3. Los Alamos National Laboratory has discussed developing a physics/chemistry-based modal emission model for use in the TRANSIMS planning model, which is also three to four years away from completion.

As discussed earlier, the analysis demonstrated in the following sections can be applied in the future to the modal emission models described above. Not only would this result in a more equitable allocation of costs between vehicle classes, but such an analysis would also permit the allocation of costs based on the emissions resulting from driver behavior and different levels of congestion.

5.2 Equivalency Factors -- HC, CO, NO_x (EF_p)

As discussed in Chapter 4, the calculation of the equivalency factor involves identifying the contribution of a given vehicle to the overall emission level under certain stated conditions. The equivalency for a certain pollutant, or EF_p, relates the number of additional vehicles of one class required to produce the same amount of pollutants as one vehicle of a base class, all else remaining equal. The EF_p can be derived by solving the equality shown in Equation 5-1.

[5-1] $$\frac{dE_p}{dVC_i} = EF\_p_{i-A} \frac{dE_p}{dVC_A}$$

where:

E Emissions of a certain pollutant, p

EF_p_{i-A} Equivalency factor for pollutant p for given vehicle class i to a

LDGV with a base model year, altitude, mileage accumulation, and speed, designated A

VC_i Volume of vehicle class i

VC_A Volume of LDGV A

In the following discussion, EF_p's have been derived for three pollutants: HC, CO and NO_x.

There are a multitude of ways of applying the equality of Equation 5-1 using the MOBILE5a model. Table 5-2 shows the different possibilities from which a base case must be chosen. The EF_p's presented below are all based on a LDGV of a specific model year with a specific mileage travelling at 20 mph. A speed of 20 mph is used as a base because emission rates that are not corrected for speed are based on the average speed of the FTP cycle, which is 19.6 mph.

Table 5-2. Choices on Which to Base EF_p.

Parameter	Choices
Vehicle Type	LDGV, LDGT1, LDGT2, HDGV, LDDV, LDGT, HDDV, MC
Model Year Groups	1967-2020 (many years excluded)
Mileage Accumulation	0-40,000; 50,000+ miles
Speeds	0-65 mph
Altitudes	Low (represented by 500 ft. - used in almost all urban areas), High (5500 ft.)
Other (towing, air conditioning, humidity, fuel volatility, etc.)	-

5.2.1 Vehicle Emissions and the Resultant EF_p

The EF_p's are directly linked with the emissions that the MOBILE5a model uses as its foundation. Figures 5-2, 5-3 and 5-4 illustrate the decrease in LDGV emissions since 1968.

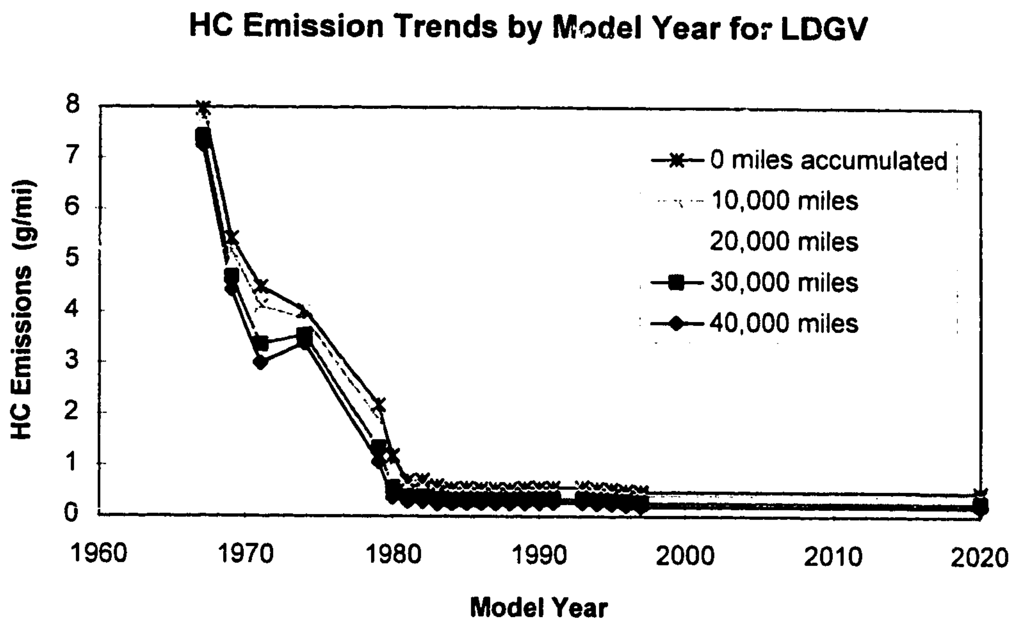

Figure 5-2. Variation in HC Emissions from LDGV with Model Year

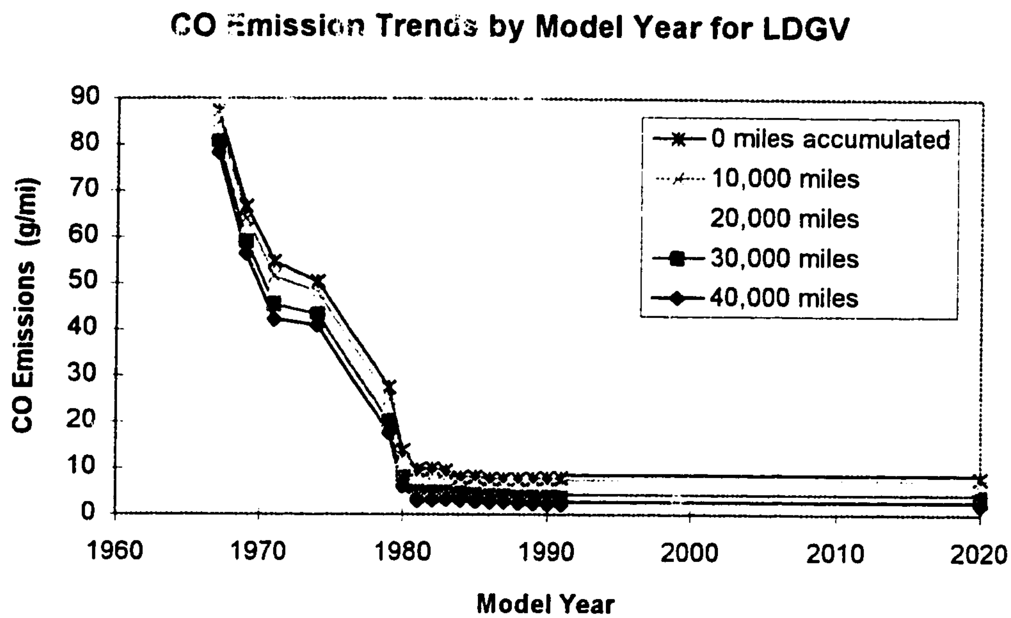

Figure 5-3. Variation in CO Emissions from LDGV with Model Year

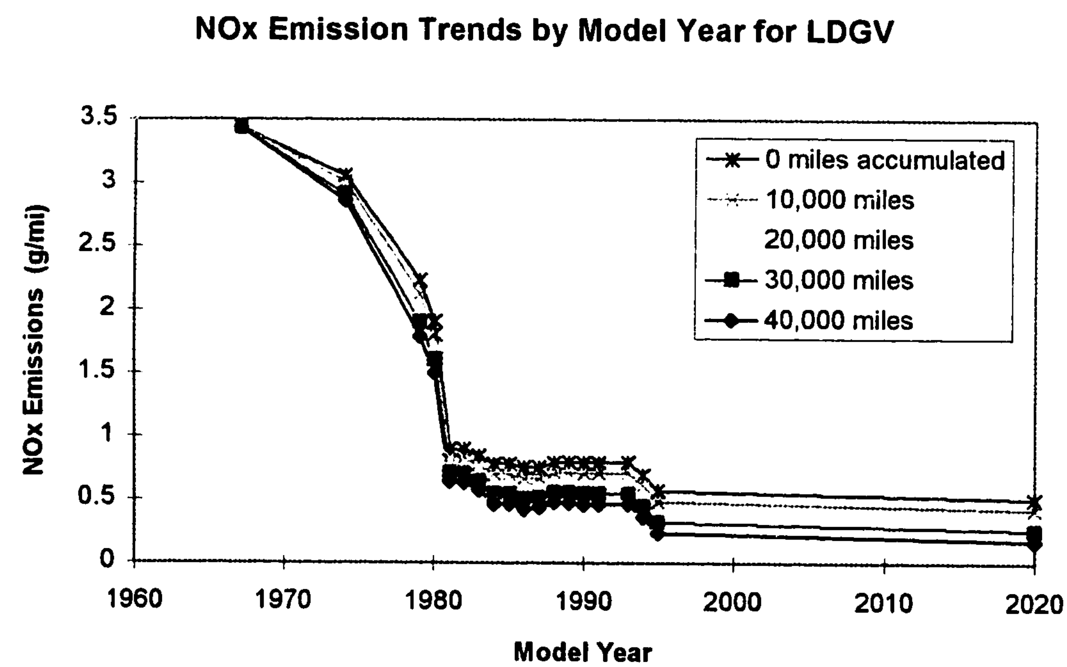

Figure 5-4. Variation in NO_x Emissions from LDGV with Model Year

Although the rates of deterioration with mileage accumulation remain the same, CO and HC emissions decrease dramatically between 1968 and 1980. This decrease reflects a sequence of vehicle technology improvements: after 1966, manufacturers were required to make the combustion of fuel in the engine more efficient; evaporative emission controls were introduced in the early 1970's; in 1975, catalytic converters were required on all vehicles (Washington, 1994). HC and CO emissions are relatively stable from 1983 onward. LDGV NO_x emissions, on the other hand, gradually decrease as the model year increases between 1968 and 1980, and then decrease dramatically between 1980 and 1981, reflecting the introduction of special Oxidation Reduction catalysts on vehicles in the early 1980's (Washington, 1994). Decreases in NO_x emissions are also projected for 1994 and 1995.

It was noted in Table 5-2 that altitude can determine a vehicle's EF_p. Figures 5-5, 5-6 and 5-7 show that the relationship between high altitude and low altitude emissions varies widely from year-to-year for all three criteria pollutants. In 1970, the low-altitude emissions of HC and CO are roughly two-thirds the magnitude of high-altitude emissions. In the mid-1980's and through the 1990's, the low-altitude and high-altitude HC and CO emissions are essentially equal. Low altitude NO_x emissions, on the other hand, are roughly two-thirds *higher* than high-altitude emissions. Low- and high-altitude NO_x emissions are also essentially equal after 1984.

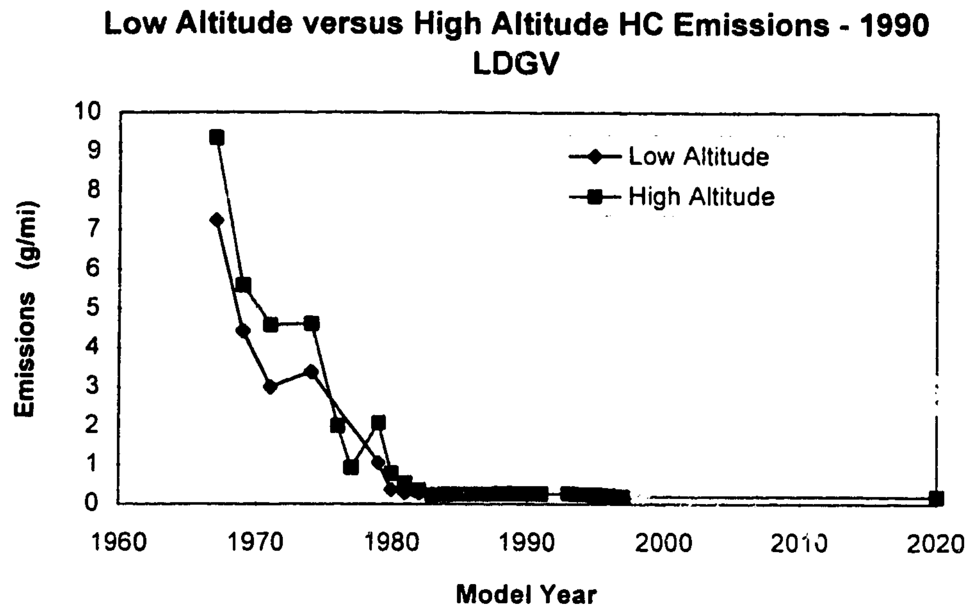

Figure 5-5. Comparison of Low and High Altitude HC Emissions

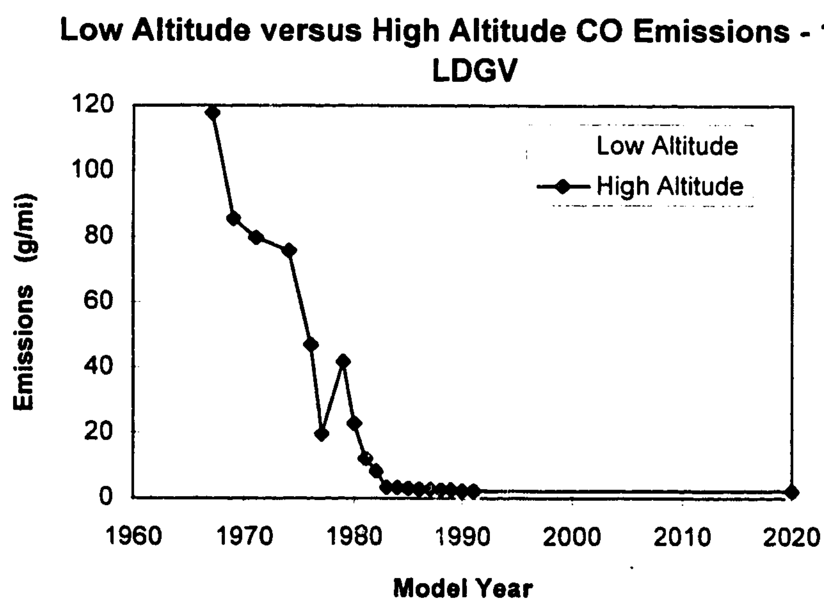

Figure 5-6. Comparison of Low and High Altitude CO Emissions

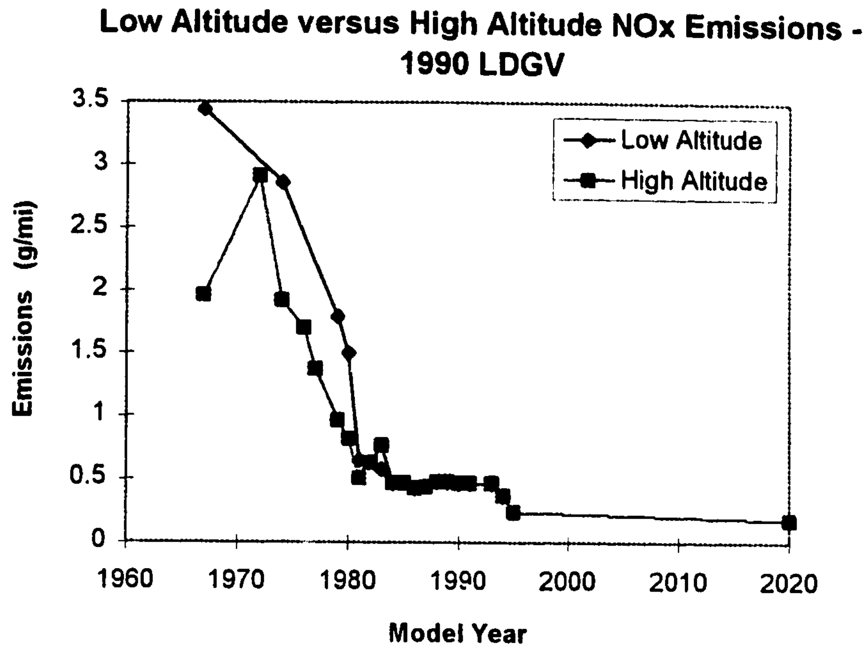

Figure 5-7. Comparison of Low and High Altitude NO_x Emissions

The abrupt reversal in the decreasing trend of emissions in the late 1970's in HC and CO emissions is not exhibited by the chart of NO_x emissions.

In Figures 5-8, 5-9 and 5-10 the HC emissions of LDGV and LDGT1 are contrasted over the model years.

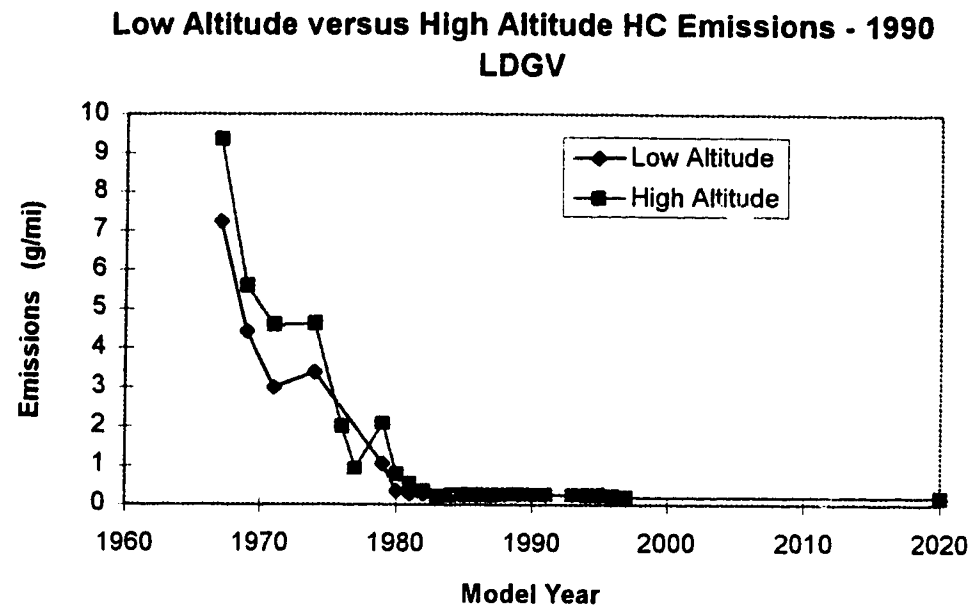

Figure 5-8. Low and High Altitude HC Emissions for LDGV

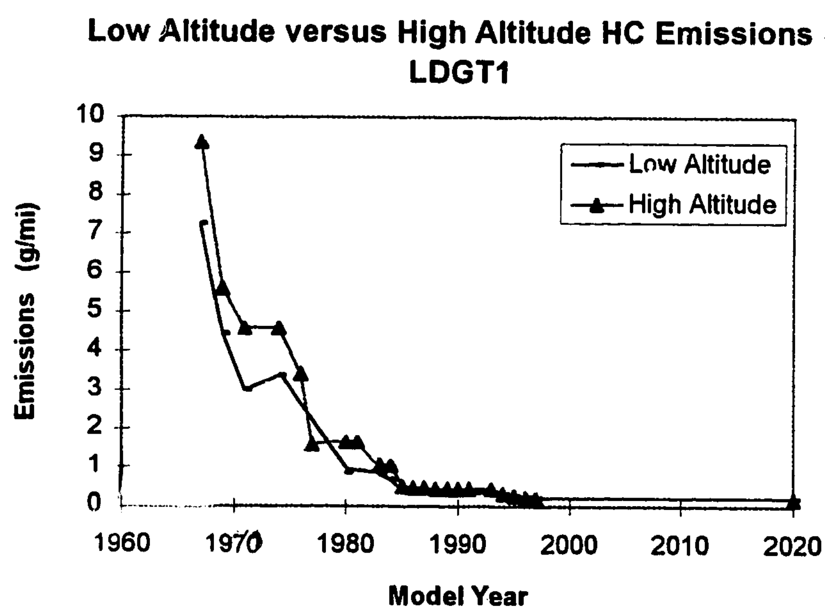

Figure 5-9. Low and High Altitude HC Emissions for LDGT1

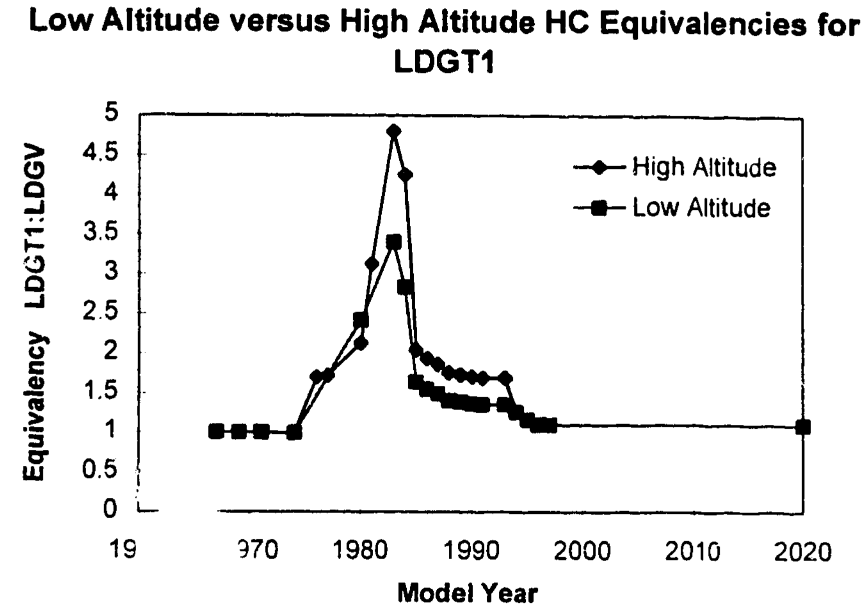

Figure 5-10. Low and High Altitude EF_HC's for LDGT1

Both vehicle classes have similarly decreasing emissions up until 1980. From 1980 to 1985, the HC emissions from LDGT1 are 1 to 1.5 grams per mile higher than those from LDGV. This does not appear to be a large difference relative to the emissions in the late 1960's and early 1970's. However, when an EF_HC (X model year) is plotted, as in Figure 5-10, the relative contribution to emissions by the LDGT1 class is clear. For the high-altitude scenario the EF_HC (X model year) peaks at 4.8 in 1983, reflecting the low level of HC emissions attributed to LDGV.

It is notable that the equivalencies of LDGT1 at low altitudes are less than that at high altitudes, and that this difference is significant between 1974 and 1994. This

This suggests that equivalencies determined in one jurisdiction are not transferable to another jurisdiction at a different altitude.

Low and high altitude HDDV emissions are plotted in Figure 5-11.

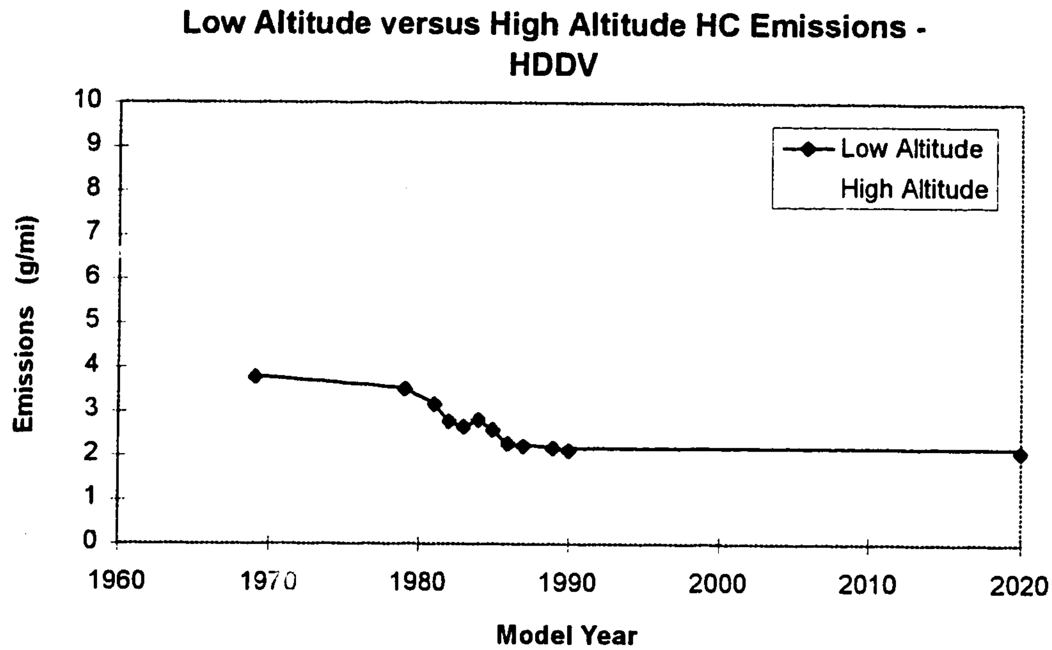

Figure 5-11. Low versus High Altitude HC Emissions for HDDV

The difference between low altitude and high altitude emissions is even more apparent in the HDDV class. High altitude HC emissions are 2.5 times as high as low altitude emissions, regardless of the model year.

As mentioned in the first section of this chapter, there are eight vehicle classes used in the MOBILE model. The EF_HC's of four of these vehicle classes are plotted in Figure 5-12. The EF_HC's of four major vehicle classes are plotted on this chart.

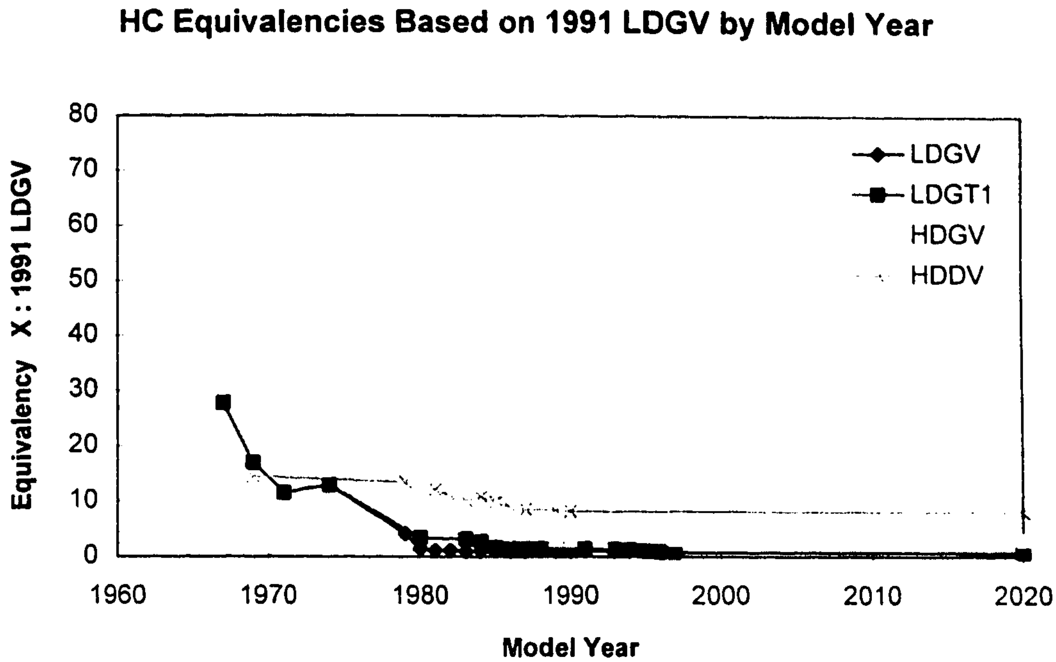

Figure 5-12. Variation in EF_HC by Model Year

The EF_HC's of all four vehicle classes decrease as the vehicle model years increase, reflecting the improvements in vehicle technology in all vehicles. HDDV show the least variation in EF_HC over the model years. Note that before 1970, the EF_HC of HDDV is much less than that of LDGV, LDGT1, and HDGV. The EF_HC of HDGV, on the other hand, decreases from 74 in the 1970 model year to 3 in 1990. The variation in the EF_HC of LDGT1 is still apparent between 1980 and 1985 even when the EF_HC is indexed to 1991. The EF_HC's for the 1990 model year are 1.0 for LDGV, 1.4 for LDGT1, 3.1 for HDGV, and 8.2 for HDDV. Little change in the EF_HC will occur in the near future based on the projections of the MOBILE5a emission rates.

As in the case of the EF_HC, the EF_CO generally decreases over the model years in each vehicle class. Figure 5-13 shows how the EF_CO for the same four vehicle classes decreases as the model year increases.

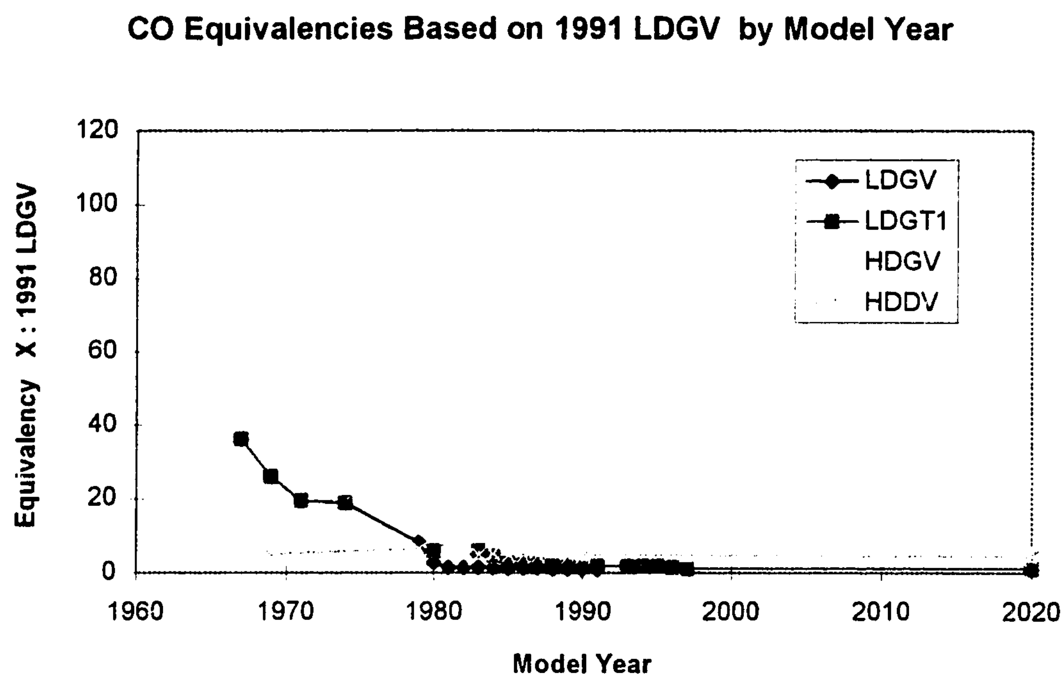

Figure 5-13. Variation in EF_CO by Model Year

The greatest variation is in the HDGV class, where the EF_CO decreases from 115 to 25 between 1974 and 1984. In the 1990 model year, the EF_CO's are 1.0 for LDGV, 1.8 for LDGT1, 5.2 for HDGV, and 4.5 for HDDV.

The plot of the EF_NO_x is shown in Figure 5-14.

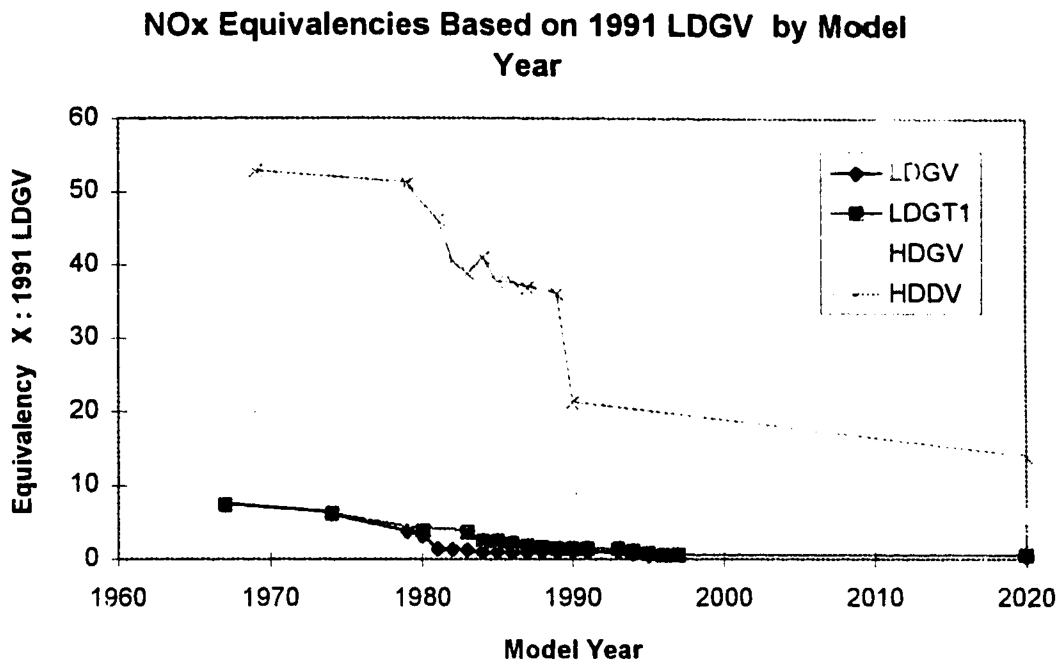

Figure 5-14. Variation in EF_NO_x by Model Year

The EF_NO_x is much higher than the EF_CO and the EF_HC in the case of HDGV and HDDV. All of the vehicle class EF_NO_x's decrease as the model years increase. In 1990, the EF_NO_x's are 1.0 for LDGV, 1.4 for LDGT1, 9.2 for HDGV, and 21.2 for HDDV. Heavy duty vehicles bear more responsibility for NO_x emissions relative to CO and HC emissions.

In the figures displayed thus far, the base for the calculation of the EF_p has been a LDGV with 0 miles accumulated. The EF_p is calculated separately for each mileage accumulation group to create Figures 5-15, 5-16 and 5-17. For example, to determine an EF_HC for a 1984 HDDV with 10,000 miles accumulated, the emissions of the HDDV are compared to those of a 1990 LDGV with 10,000 miles accumulated. For a 1984 HDDV with 20,000 miles accumulated, the emissions are compared to those of a LDGV with 20,000 miles accumulated, and so on. These charts are useful in indicating that the more mileage a vehicle accumulates, the closer its emissions come to those of a LDGV. For instance, the EF_HC of a HDDV with 0 miles accumulated is approximately 8, whereas its EF_HC with 40,000 miles accumulated is 4. The same trends can be seen in the plots of the EF_CO and EF_NO_x values. However, if the EF_HC is based on a vehicle with 0 miles accumulated in all cases, the plot of EF_p will be different. In Figure 5-15 the EF_HC is based on a 1991 LDGV with 0 miles accumulated. Calculated in this manner, the *relative* responsibility of each vehicle class decreases as mileage is accumulated.

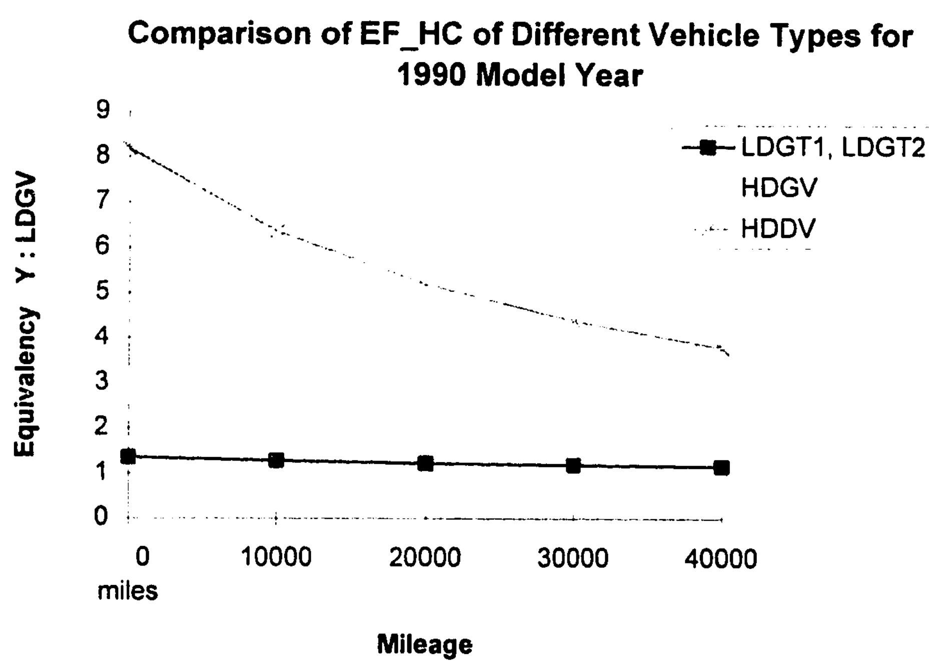

Figure 5-15. Illustration of EF_HC Decline with Mileage Accumulation

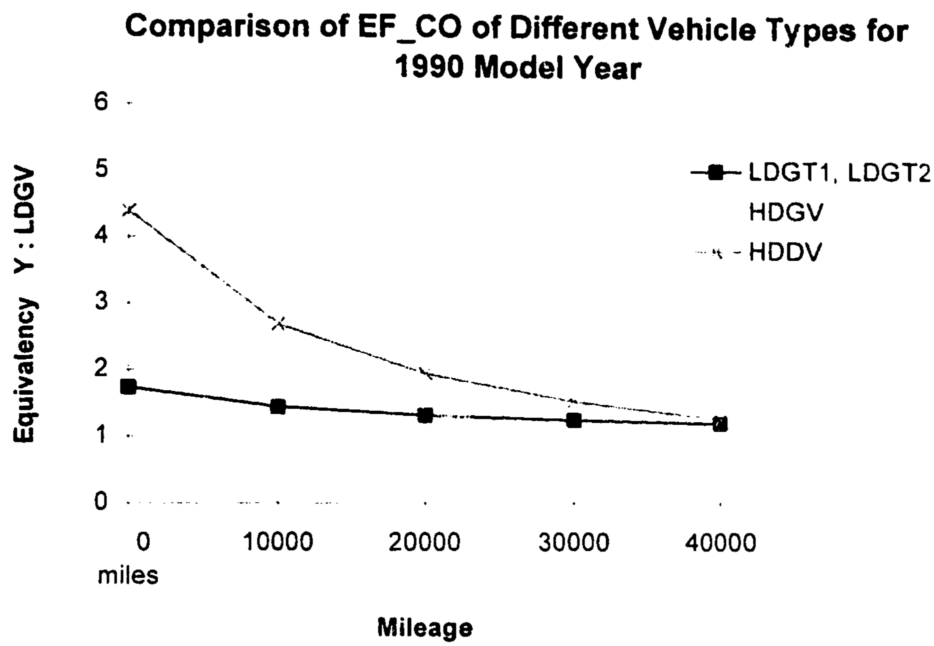

Figure 5-16. Illustration of EF_CO Decline with Mileage Accumulation

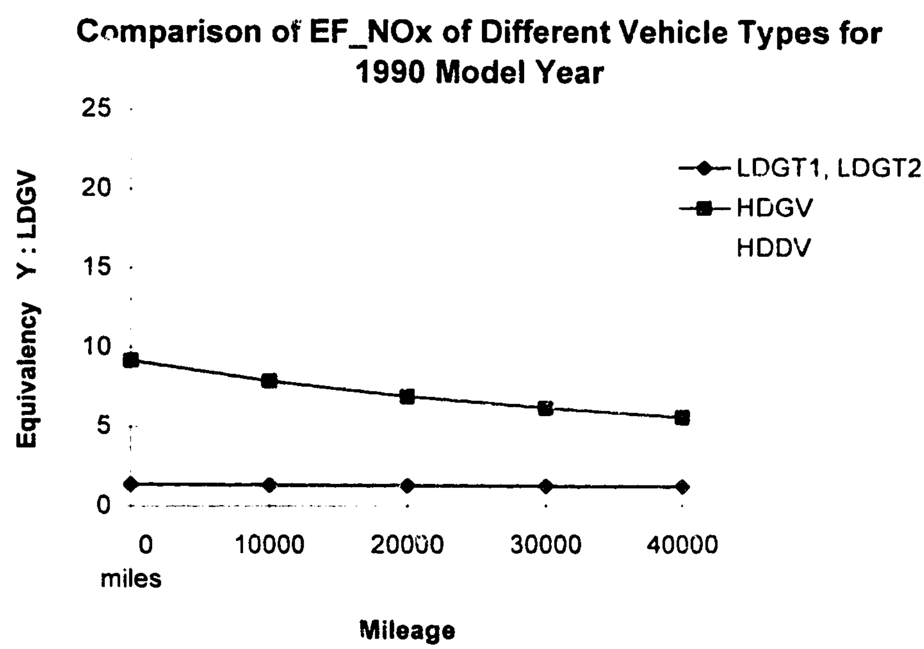

Figure 5-17. Illustration of EF_NO_x Decline with Mileage Accumulation

Note that emissions on a gram-per-second basis are not illustrated by the charts shown in this chapter. A long trip at high speeds may result in the same overall level of pollutant emissions as a short trip at slower speeds. From the perspective of reducing CO_2 emissions or overall pollution levels, neither trip is preferred over the other. Gram-per-mile or per-kilometer emission estimates are used because the output from transportation planning models is the amount of vehicle travel in miles or kilometers. These travel estimates can be multiplied by a gram-per-mile or per-kilometer emission rate to obtain overall emission concentrations.

5.2.2 The Effect of Speed Corrections on EF_p's

The following results document the application of speed correction factors to the basic emission rates. Speed correction factors (SCF's) are only available for LDGV, LDGT1 and LDGT2, due to testing constraints such as vehicle size. LDGT1 and LDGT2 SCF's are based on LDGV SCF's with adjustments for differences in emission control technology from year to year. The SCF's have only been estimated for the years between 1979 and 1992. For the years prior and following this range, the 1979 and 1992 SCF's are applied respectively. There are two equations used to calculate SCF's within the MOBILE5a program. These equations correspond to two speed ranges, one low-speed (<19.6 mph) and one mid-range (19.6<speed<48.0 mph). For HC and CO, the same equation constants used for 48 mph are used for speeds in the range of 48-55 mph, but not for NO_x. The section from which the SCF's were extracted to perform this analysis are shown in Appendix D. High speed correction constants, corresponding to a speed of 65 mph, are used in the model but do not correspond to the same model years as the SCF equations. The 65 mph constant corrections are left out of this analysis.

Figure 5-18 shows the variation in the EF_HC with speed.

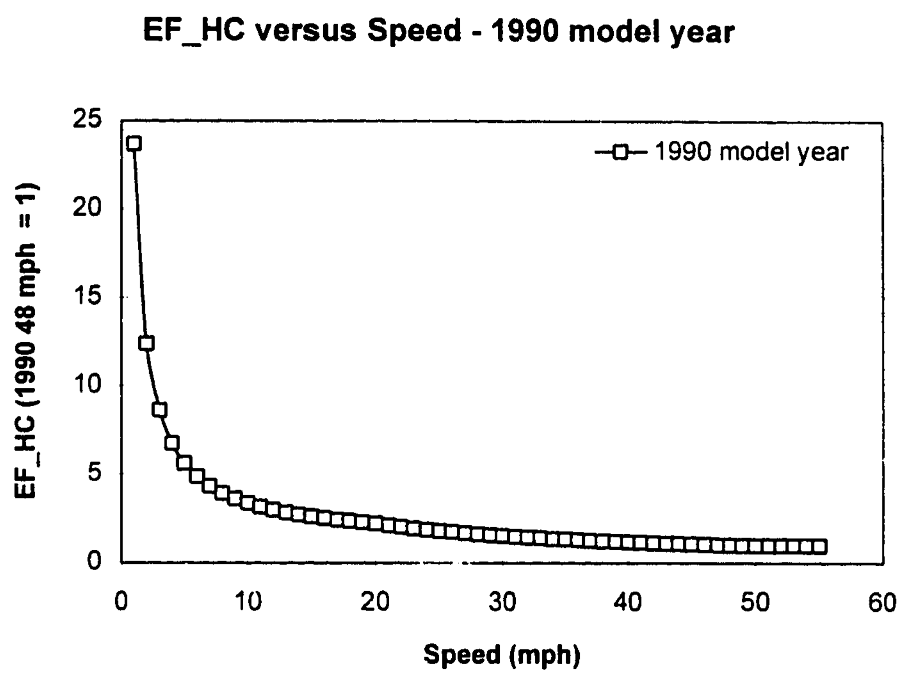

Figure 5-18. EF_HC Versus Speed

It may be seen that an automobile travelling at 10 mph is responsible for roughly 3.5 times the emissions of the an automobile travelling at 48 mph. The greatest decrease in HC emissions occurs between 0 and 10 mph. HC emissions also decrease between 10 mph and 55 mph according to the model. The slight discontinuity in the curve at 20 mph indicates the transition between the SCF equation used in the speed range 0-19.6 mph and that used for 19.6-48 mph in the MOBILE5a model. The same SCF equation parameters are used in the range of 48-55 mph for HC and CO, resulting in a straight line between 48 and 55 mph.

The wide variation in EF_HC's with speed, depending on the model year of the automobile, is illustrated in Figure 5-19.

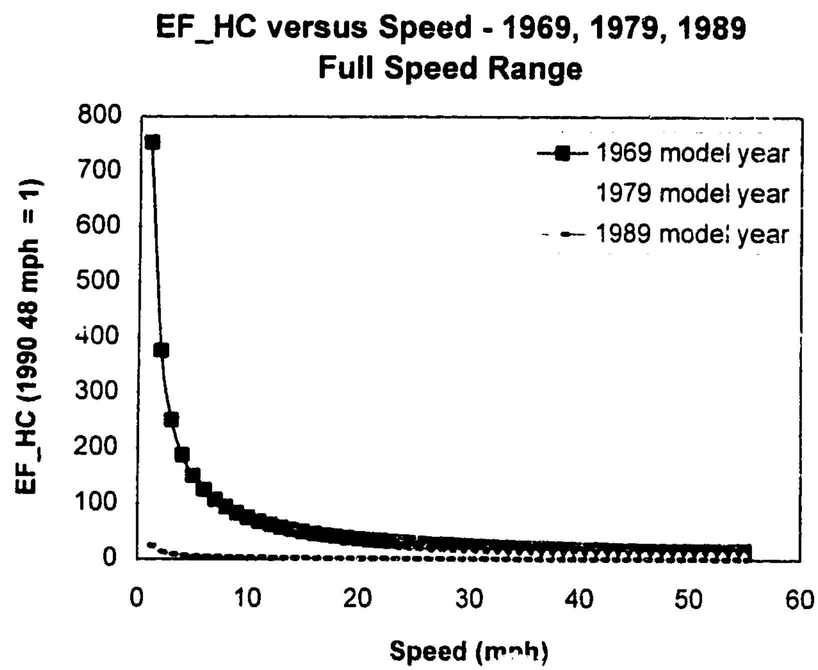

Figure 5-19. EF_HC Versus Speed for Different Model Year Groups

For example, the EF_HC for a 1969 automobile ranges from 75 at 10 mph to 38 at 20 mph and to 16 at 48 mph. A 1979 automobile is responsible for roughly one quarter of the emissions of a 1969 automobile at any given speed. A 1989 automobile is responsible for roughly one fifteenth of the HC emissions of the 1969 automobile.

The effect of speed on the EF_HC is pronounced even in the region of relatively low-sloped curves between 20 and 48 mph where the mid-speed equation is applied. Figure 5-20 shows that the EF_HC decreases by a factor of 2 between 20 mph and 48 mph for all three model year automobiles.

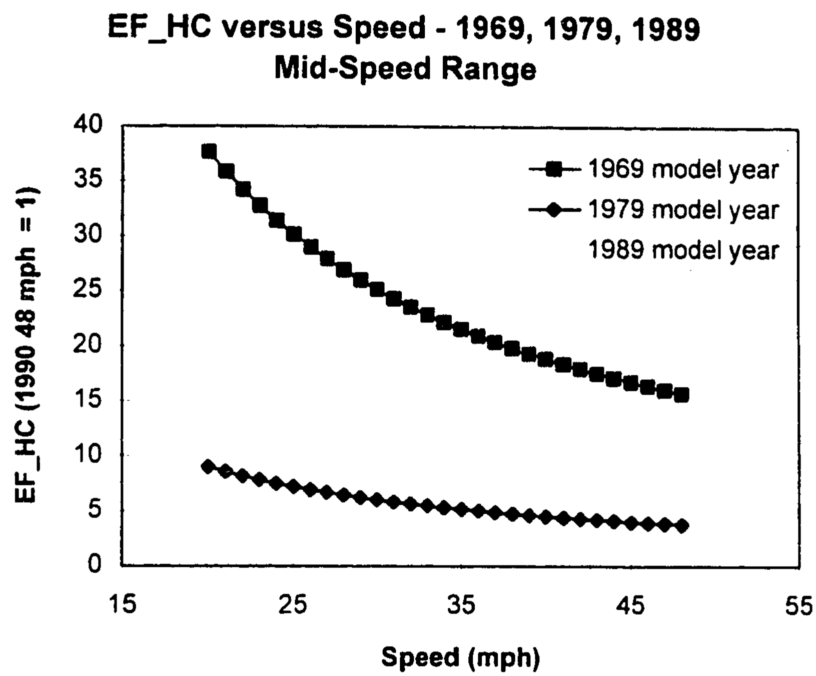

Figure 5-20. EF_HC Versus Mid-Range Speeds

Figure 5-21 shows that the EF_HC's for more recent model years, between 1986 and 1996, do not differ by more than 2.0.

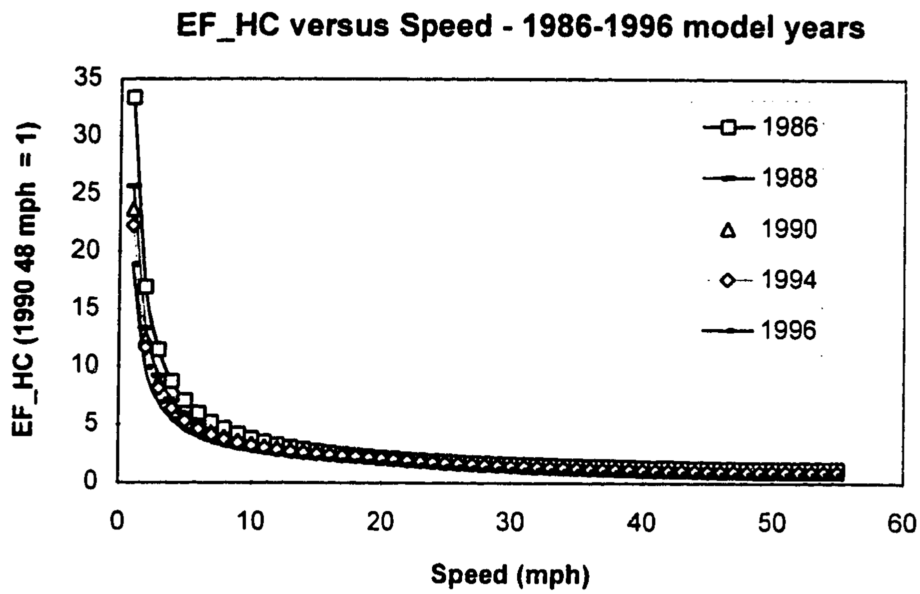

Figure 5-21. EF_HC Versus Speed for 1986-1990 Model Year Groups

The difference in EF_HC's between 1986 automobiles and 1996 automobiles is small compared to the difference between 1969 and 1979 or 1979 and 1989 as illustrated in Figure 5-19. The effect of speed on the EF_HC does not differ greatly between the model years shown.

Figure 5-22 illustrates the effect of slow speeds on gram-per-mile CO emissions from light-duty vehicles.

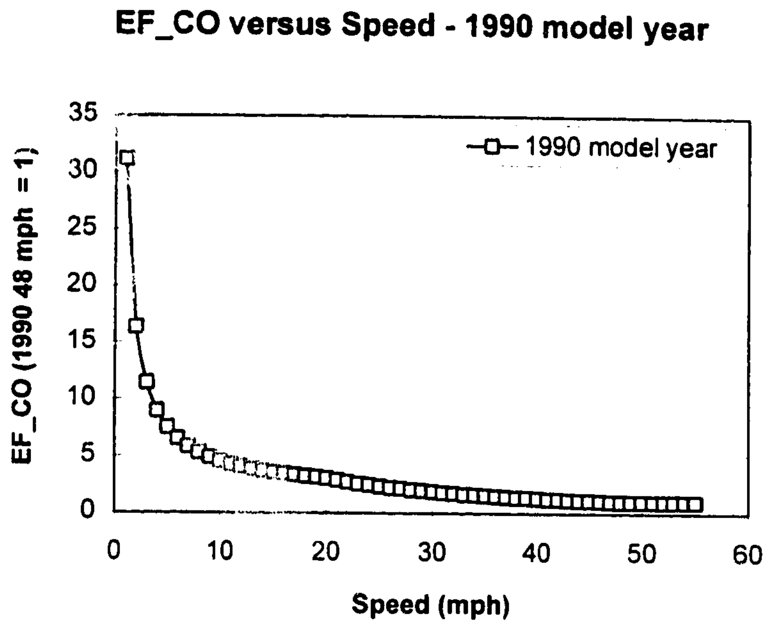

Figure 5-22. EF_CO Versus Speed

The exponential decrease of the 1990 model year vehicle EF_CO parallels that of the same vehicle's EF_HC. The EF_CO is slightly higher at slow speeds than the EF_HC, shown in Figure 5-18.

Figure 5-23 illustrates once again the magnitude of the improvement in vehicle emissions that has been made since 1969.

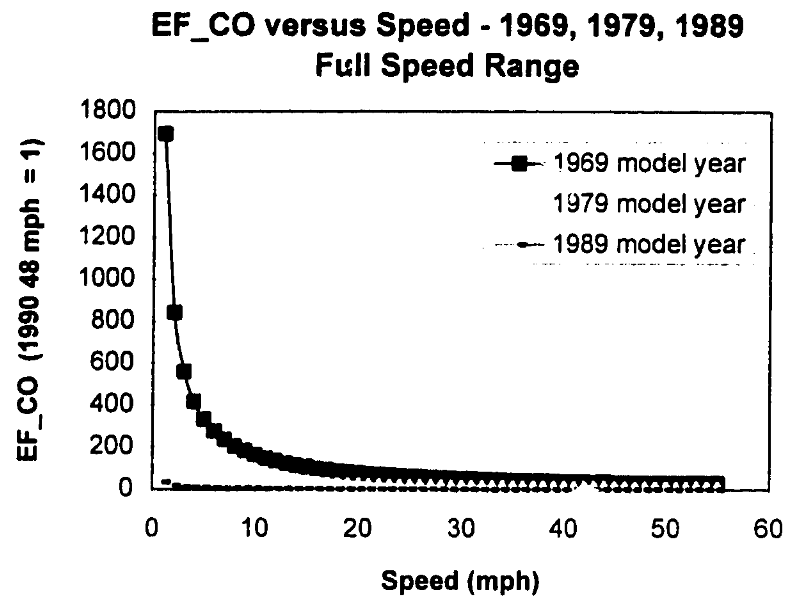

Figure 5-23. EF_CO Versus Speed for Different Model Year Groups

The responsibility of older vehicles for CO emissions decreases as speeds increase. For example, a 1969 model year automobile travelling at 10 mph is responsible for roughly 32 times as many emissions as a 1990 automobile travelling the same speed. At 48 mph, the 1969 automobile is responsible for 26 times the CO emissions as the 1990 automobile. As well, a 1979 automobile travelling 10 mph is responsible for roughly 10 times as many CO emissions as a 1990 model year automobile travelling the same speed. At 48 mph, the 1979 vehicle is responsible for 8 times as many CO emissions. The difference in EF_CO between model years decreases exponentially as average speed increases.

Figure 5-24 depicts the EF_CO within the range of the mid-speed speed correction factor equations, between 20 and 48 mph.

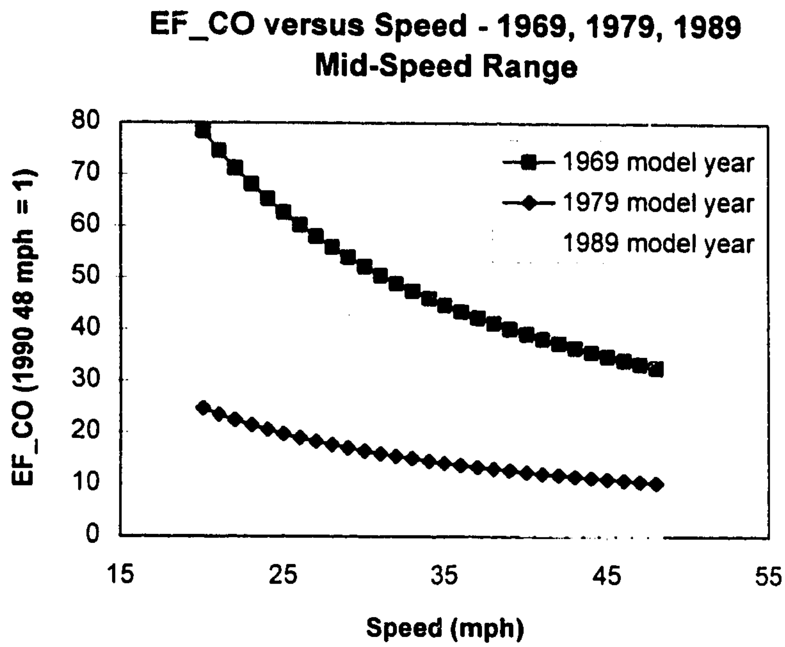

Figure 5-24. EF_CO Versus Mid-Range Speeds

The EF_CO of a 1969 automobile travelling 20 mph is 78, significantly higher than that of a 1979 automobile, 25, and that of a 1989 automobile, 3. Almost eighty 1990 vehicles travelling at 48 mph emit the same amount of CO as one 1969 vehicle travelling at 20 mph. The responsibility for CO emissions of all of the vehicles decreases by a factor of 2 between 20 and 48 mph. Thus, even in the range of 20 to 48 mph, the effect of the average speed is significant.

Figure 5-25 illustrates that the EF_CO relationship with speed is very similar between model years 1986 and 1990.

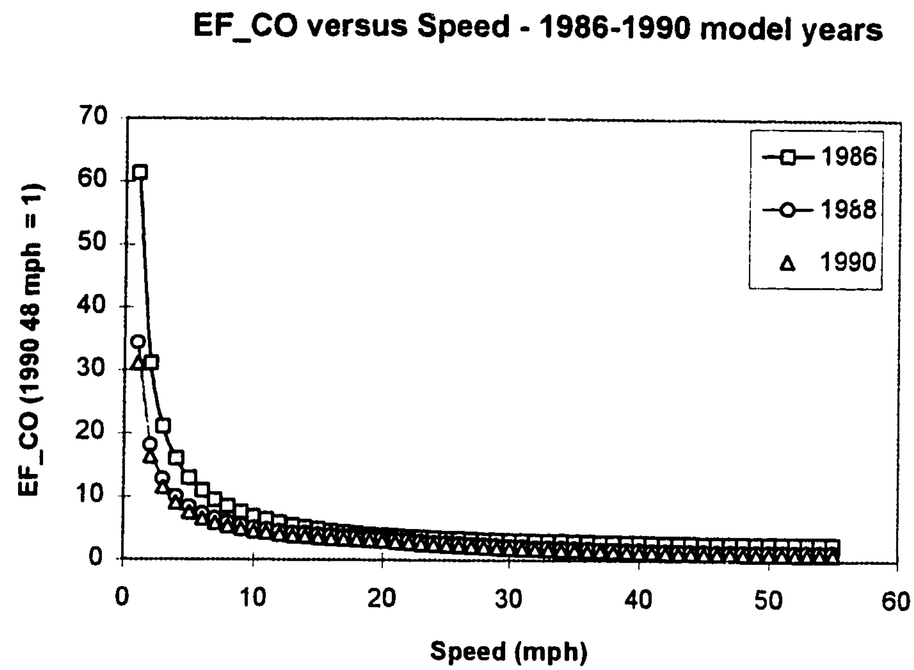

Figure 5-25. EF_CO Versus Speed for 1986-1990 Model Year Groups

There is little difference between the EF_CO for 1989 and 1990 automobiles. A 1986 model year vehicle is still responsible, however, for over twice the CO emissions of a 1990 vehicle at speeds above 40 mph. Comparing this chart with Figure 5-23, it is clear that the greatest individual emission improvements were the result of the addition of catalytic converters in the 1970's. Emissions from individual LDGV's have been decreasing continuously since the 1960's, but at a decreasing rate. The engine technology improvements made since 1986 result in significant emission reductions, but none on the scale of the gains between 1969 and 1980.

Speed is shown to have far less influence on NO_x emissions as on CO or HC emissions. As illustrated in Figure 5-26 the EF_NO_x for automobiles travelling at speeds under 10 mph is much closer to 1 than the EF_CO or the EF_HC; in the case of 1990 model year automobiles, the EF_NO_x at 10 mph is 1.0.

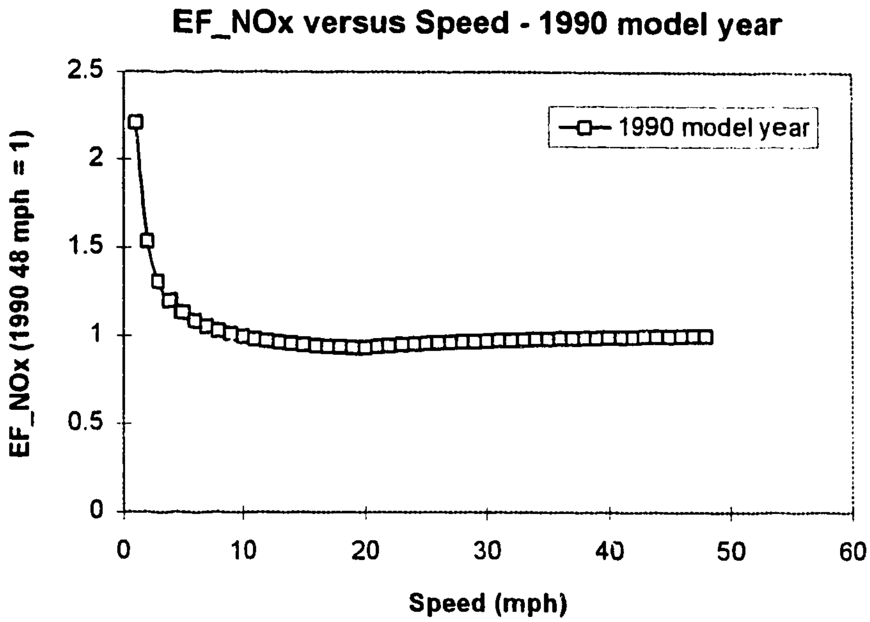

Figure 5-26. EF_NO_x Vers

The EF_NO_x continues to decrease, even dipping below 1.0, until the average speed reaches 20 mph, where the mid-range speed correction factor equation is applied. The EF_NO_x increases from 0.93 at 20 mph to 1.0 at 48 mph. Note that this increasing trend in the range of 20 to 48 mph differs from that of the EF_HC and EF_CO. This is partially explained by the origin of the pollutants. HC and CO are products of the incomplete combustion of fuel, whereas NO_x is formed when combustion occurs at high temperatures.

The EF_NO_x is much lower for 1979 and 1969 model year vehicles than in the case of HC or CO. However, older vehicles are still far more responsible for NO_x emissions than recent models. For example, as shown in Figure 5-27 , at 10 mph a 1967 model year automobile is responsible for roughly 7.5 times the emissions of a 1989 vehicle, and 2 times the emissions of a 1979 vehicle.

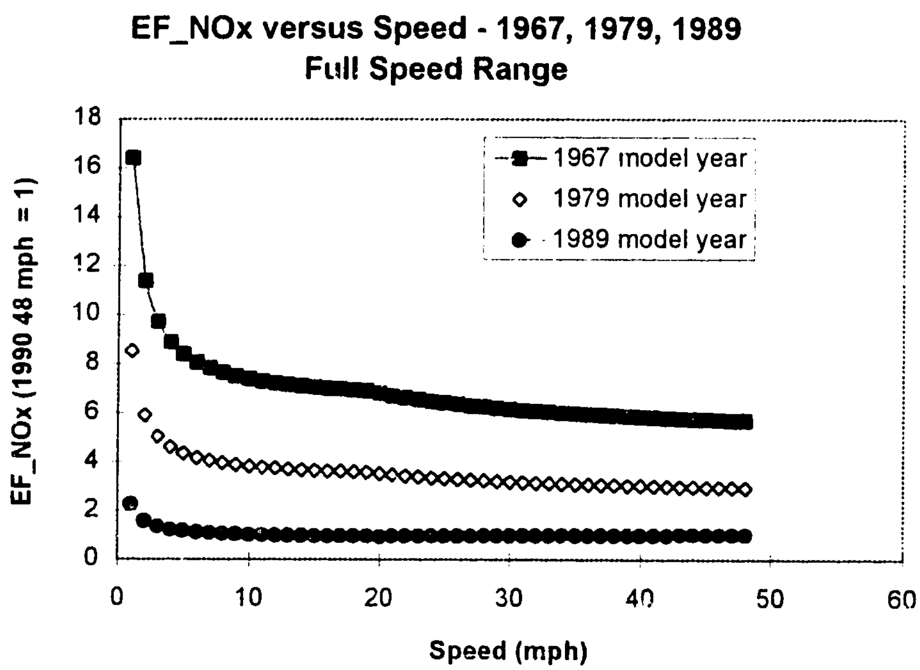

Figure 5-27. EF_NO_x Versus Speed for Different Model Year Groups

The relatively even step from the EF_NO_x of 1967 to that of 1979 and that of 1989 suggests that the addition of Oxidation Reduction catalysts in the 1980's has been almost as significant in improving NO_x emissions as the addition of the original catalytic converters in the 1970's.

Figure 5-28 is a comparison of EF_NO_x's for three sets of model year groups.

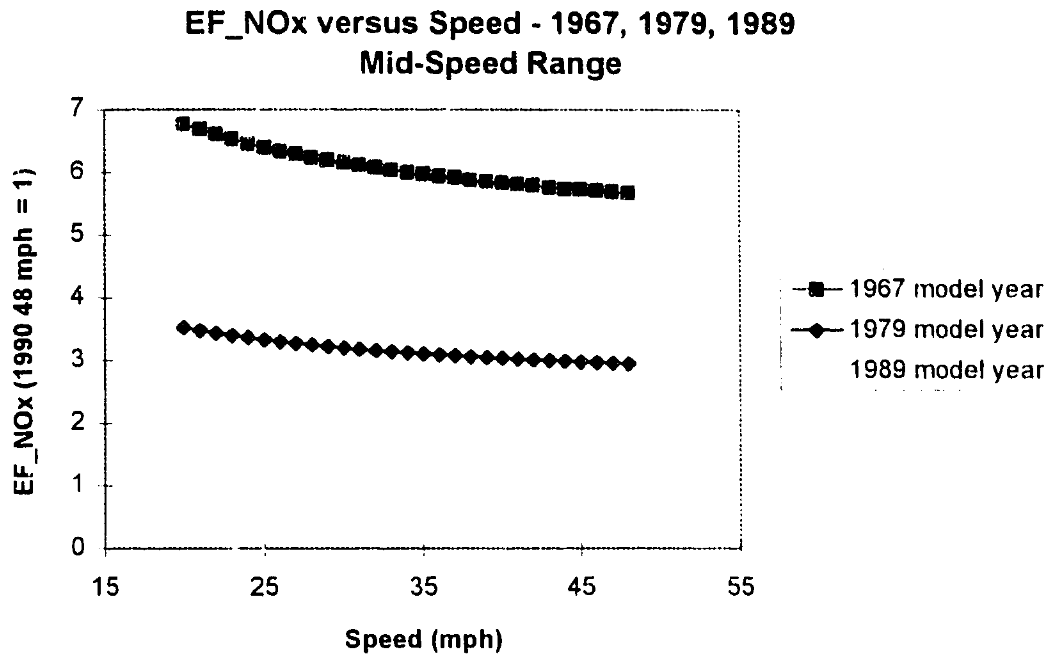

Figure 5-28. EF_NO$_x$ Versus Mid-Range Speeds

In the speed range between 20 and 48 mph, the EF_NO$_x$ curves visibly vary between the three model years 1967, 1979 and 1989. The EF_NO$_x$ only decreases by a factor of 1.15 for a 1967 vehicle. For a 1989 vehicle, the EF_NO$_x$ actually increases slightly between 20 and 48 mph. The relationship between speed and the EF_NO$_x$ changes from a negative slope to a positive slope curve between 1979 and 1989. This is examined in more detail in Figure 5-29.

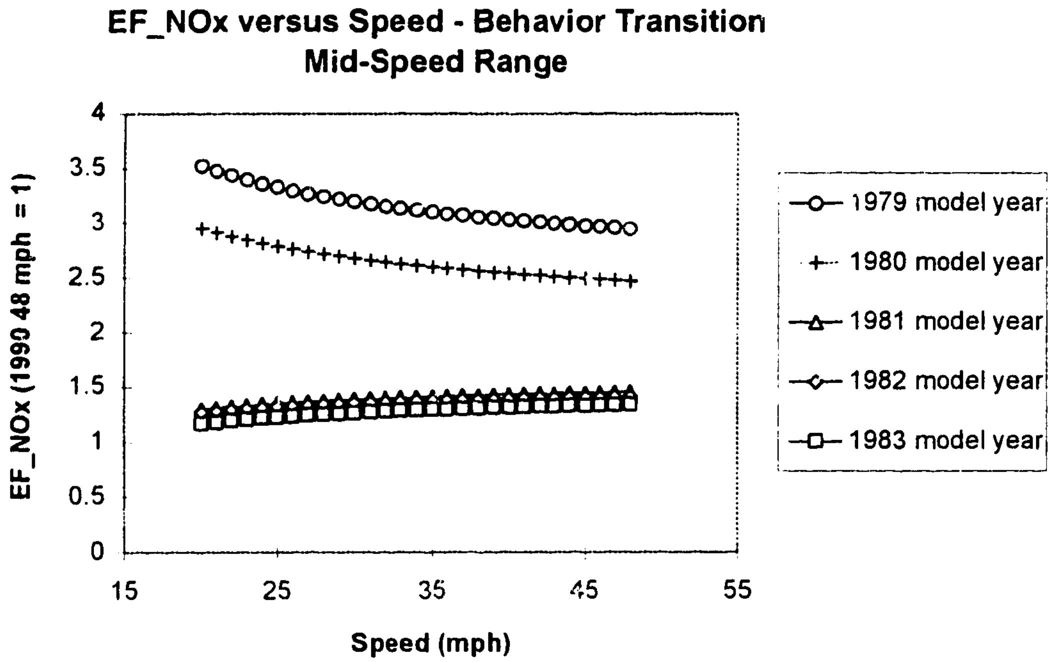

Figure 5-29. Transition in Behavior of EF_NO$_x$ with Speed

This chart shows the EF_NO$_x$ curves for the 1979, 1980, 1981, 1982 and 1983 model years. There is a significant drop in the EF_NO$_x$ between 1980 and 1981. As well, the equation relating NO$_x$ emissions and speed changes between 1980 and 1981. The 1980 equation has a positive coefficient in front of the speed variable; the 1981 equation has a negative coefficient. The EF_NO$_x$ is very similar over the entire mid-speed range for the 1981, 1982 and 1983 model years.

Figure 5-30 illustrates how close the EF_NO$_x$ values are for more recent model years, 1986 to 1994.

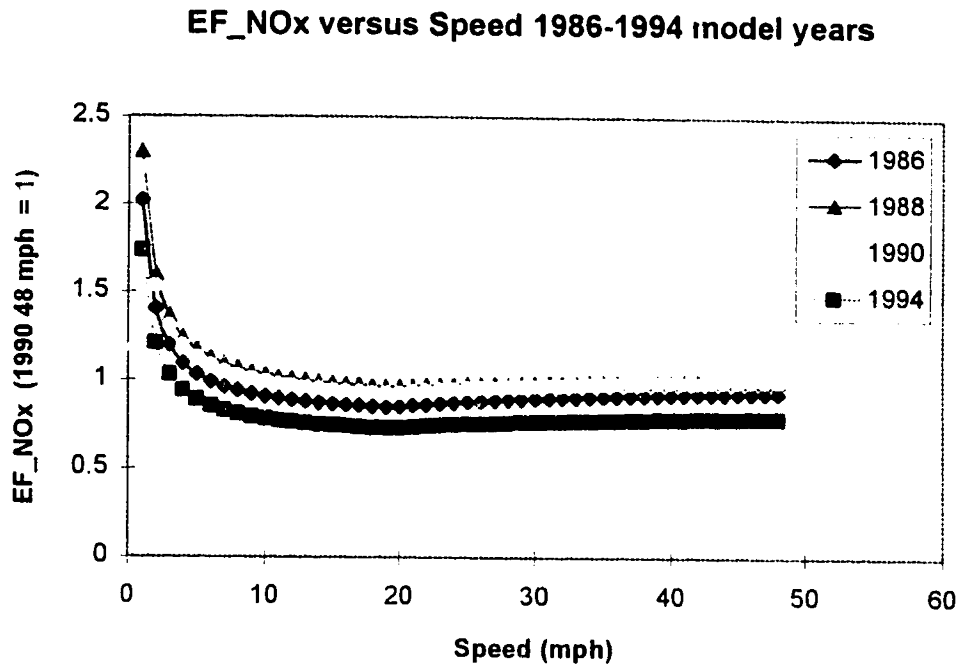

Figure 5-30. EF_NO_x Versus Speed for 1986-1990 Model Year Groups

At speeds higher that 20 mph, all of the model years' EF_NO_x's are between 0.78 and 1.1. The significant improvements in NO_x emissions anticipated for the 1994 model year are enough to bring the EF_NO_x below 0.[illegible] at 20 mph.

5.3 Sample Problem

The sample problem that was discussed in Chapter 4 is revisited in this section. A new proposal has been forwarded that would charge vehicles on the basis of their pollutant emissions in addition to recouping the costs of noise barrier construction. Once again, it is assumed that the costs discussed in this example will be collected from road users using electronic toll collection technology.

This example serves to demonstrate the difficulty of equitably allocating costs on the basis of pollutant emissions. As discussed in Chapter 3, great difficulty is encountered in establishing the benefits of air pollution abatement. Charging road users for each separate pollutant and allocating the costs on the basis of each vehicle's emission of each pollutant is the ideal approach, as discussed in earlier sections. This example serves as a demonstration of how EF_p's might be applied and the inherent relationships between vehicle classes. With this in mind, a single value for the cost of air pollution is assessed to the road users, and this value is allocated to several different groups of road users the EF_HC, EF_CO, and EF_NO_x one at a time.

The different road user groups are shown in Table 5-3. The vehicle classes of automobiles and heavy trucks that are used in Chapter 4 are converted directly into the LDGV and HDDV classes for this analysis. Within these classes, vehicles are divided into different model year groups. These model year groups are based on the US registered automobile fleet as of July 1, 1994 (AAMA, 1995). To simplify the analysis, a median model year group is chosen for each model year group.

Table 5-3. Percent of Vehicles in Each Model Year Group used in Sample Problem

Vehicle Type	Year	MOBILE5a Model Year Group Used (MedianYear)	Percentage of Heavy Trucks 10% HT	5% HT	2.5% HT
LDGV	=< 1979	1974	11.52	12.16	12.48
	1980-82	1981	7.92	8.36	8.58
	1983-85	1984	15.48	16.34	16.77
	1986-88	1987	20.43	21.57	22.13
	1989-91	1990	18.72	19.76	20.28
	1992-95	1993	15.93	16.82	17.26
HDDV	=< 1979	1974	1.28	0.64	0.32
	1980-82	1981	0.88	0.44	0.22
	1983-85	1984	1.72	0.86	0.43
	1986-88	1987	[illegible]	1.14	0.57
	1989-91	1990	[illegible]	1.04	0.52
	1992-95	1993	1.77	0.87	0.44
		sum	100	100	100

Charges are calculated on the basis of each of three pollutants: HC, CO and NO_x. These charges are based on the specific percentage of each model year group for both LDGV and HDDV and their EF_p's. The EF_p's are calculated based on a 1990 LDGV with 0 miles accumulated travelling 20 mph. The charges are calculated based on the average speed of traffic on the arterial section, 40 km/h (25 mph), and then based on the average speed of the freeway section, 80 km/h (50 mph). The method of calculating the charge to individual vehicles in these scenarios is discussed in more detail below

The first step is to determine the EF_p of the individual vehicle on the basis of the following: pollutant, altitude, vehicle type, model year, mileage accumulation, and speed. To illustrate the methodology, take an EF_p calculated for HC at low altitude for a 1987 LDGV with 0 miles accumulated travelling at 40 km/h. The EF_HC is calculated for this vehicle as shown in Equation 5-2.

[5-2] $$\frac{dE_p}{dVC_i} = EF\_p_{i-A} \frac{dE_p}{dVC_A}$$

where:

E	Emissions of a certain pollutant, p
$EF\_p_{i\text{-}A}$	Equivalency factor for pollutant p for given vehicle class i to a LDGV with a base model year, altitude, mileage accumulation, and speed, designated A
VC_i	Volume of vehicle class i
VC_A	Volume of LDGV A

For the calculation example, this reduces to:

EF_HC = HC emissions (low altitude, LDGV, 1987, 0 miles, 25 mph) / HC emissions (low altitude, LDGV, 1990, 0 miles, 20 mph)

= 0.2102 g/mi / 0.2548 g/mi = 0.82

The EF_HC is then multiplied by the annual volume travelling on the road to obtain the total number of equivalents that the vehicle is worth. These equivalents are then summed over the entire range of vehicle types and model year groups that travel on the road as shown in Equation 5-3.

[5-3] $$AE = \sum_{i=1}^{n} (VC_i)(EF\_p_{i-A})$$

where:

AE	Number of equivalent vehicles in class LDGV of type A
$EF\_p_{i\text{-}A}$	Equivalency factor for pollutant p for given vehicle class i to a LDGV of type A
VC_i	Volume of vehicle class i

For the sample case, this is calculated as follows:

annual volume = 5000 veh/hr × 2 peak periods × 260 days/year = 2,600,000 veh

annual volume of 1987 LDGV = 20.43%/100 × 2,600,000 veh = 531,180 veh

EF_HC × annual volume = 0.82 × 531,180 = 435,568 1990 LDGV (20mph) equivalents

sum of LDGV, HDDV equivalents = 7,352,561 equivalents

Next, the cost of air pollution per equivalent is calculated as shown in Equation 5-4.

[5-4] $$C_{AE} = \frac{TC}{AE}(EF\_p_{i-A})$$

where:

TC	Total cost
AE	Number of equivalent vehicles in class LDGV of type A

$EF\_p_{i\text{-}A}$ Equivalency factor for pollutant p for given vehicle class i to a LDGV of type A

C_{AE} Cost per vehicle equivalent

As mentioned in Chapter 3, there is no agreement on the cost of air pollution. For the purposes of this example, the cost of air pollution is assumed to be 0.8 cents US per vehicle per kilometer (Tellis and Khisty, 1995). Over the one kilometer section in question, then, the cost per equivalent is calculated as follows:

cost per equivalent = (0.8 cents/km × 1 km × 2,600,000 vehicles) / 7,352,561 equivalents

= 0.283 cents US per equivalent

The charge to be allocated to the vehicle in question is simply the product of the EF_p and the cost per equivalent, as shown in Equation 5-5.

[5-5] $$C_i = C_{AE} \times EF\_p_{i\text{-}A}$$

where:

$EF\_p_{i\text{-}A}$ Equivalency factor for pollutant p for given vehicle class i to a LDGV of type A

C_{AE} Cost per vehicle equivalent

C_i Cost per vehicle in class i

Thus, for our sample calculation:

charge to 1987 LDGV = .82 × 0.283 cents US per equivalent = 0.23 cents US

As discussed above, this methodology is applied to the arterial section and the freeway section for each of the three pollutants. A sensitivity analysis of varying the percentage of HDDV between 10%, 5% and 2.5% is also conducted. The results are presented below.

Figures 5-31, 5-32 and 5-33 show the charge allocated to different model year groups of LDGV and HDDV based on the arterial section.

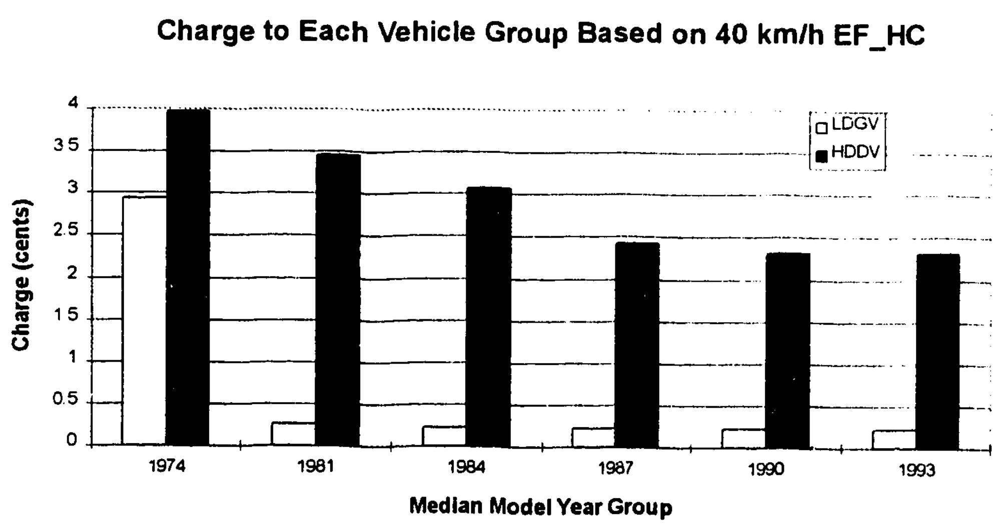

Figure 5-31. Charge Allocated Based on HC Emissions (40 km/h)

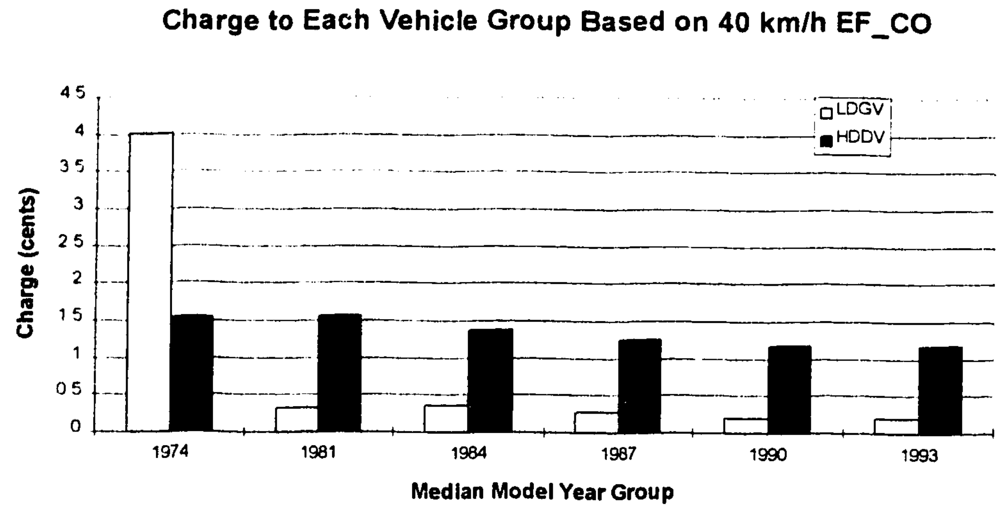

Figure 5-32. Charge Allocated Based on CO Emissions (40 km/h)

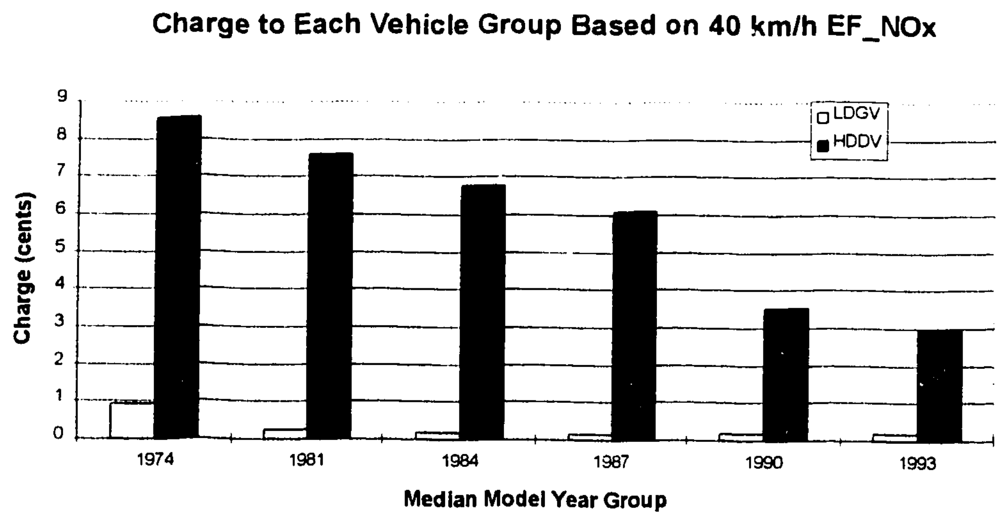

Figure 5-33. Charge Allocated Based on NO_x Emissions (40 km/h)

In Figure 5-31 a it may be seen that a HDDV is allocated at least 8 times the cost allocated to a 1981 - 1993 LDGV. However, the charge to a LDGV in the group represented by the 1974 model year exceeds that of a HDDV of model year 1987 or greater. For CO, as shown in Figure 5-32, LDGV's in most model year groups are charged one-fifth the cost allocated to HDDV, except in the 1974 group. In this group, LDGV's are allocated over 2.5 times the cost allocated to HDDV. Other than this group, the charges are similar between model year groups. As shown in Figure 5-33, the difference between LDGV and HDDV for a charge based on NO_x emissions is even greater. In this case, a HDDV would be charged between 8 and 30 times as much as a LDGV. Notice that in all three figures, the difference between the charges allocated to the two vehicle classes decreases as the model year increases.

The next three charts, Figures 5-34, 5-35, and 5-36, show that the same relationships hold for charges based on the freeway section: except for the 1974 model year group using CO emissions as a base, the charges allocated to HDDV's exceed those allocated to LDGV's by large margins, particularly in the case of NO_x. (Note that for the purposes of this example the speed correction factor equation constants for 48 mph were extended to 50 mph. This extrapolation of equation constants is done in the MOBILE5a program for HC and CO only.)

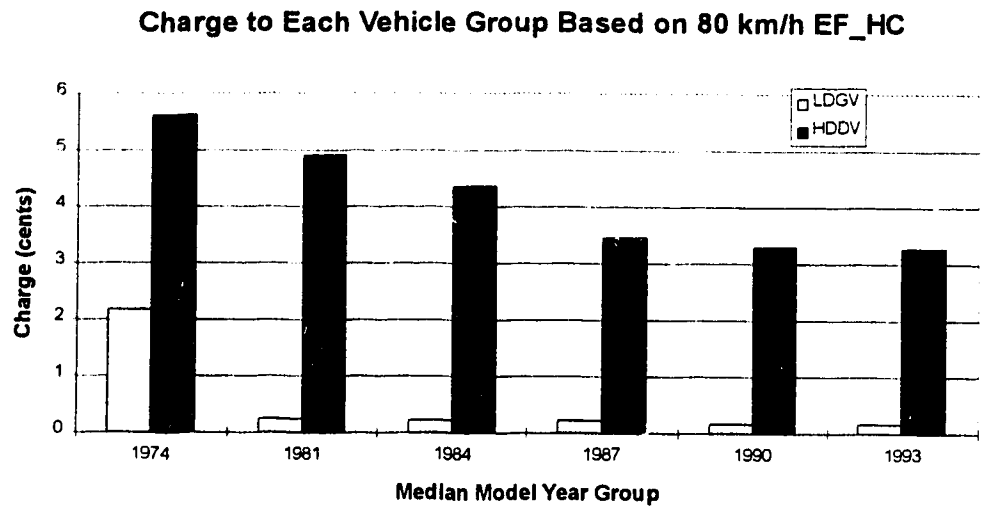

Figure 5-34. Charge Allocated Based on HC Emissions (80 km/h)

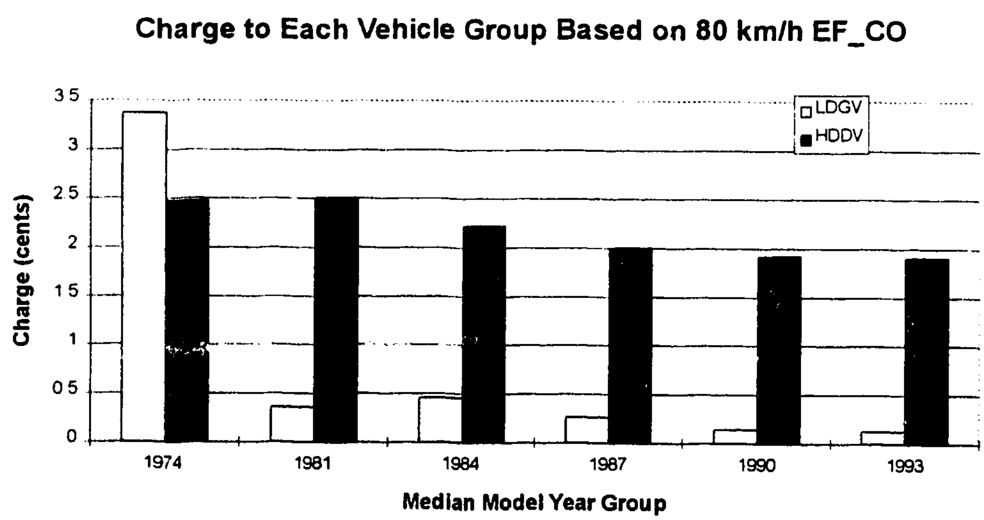

Figure 5-35. Charge Allocated Based on CO Emissions (80 km/h)

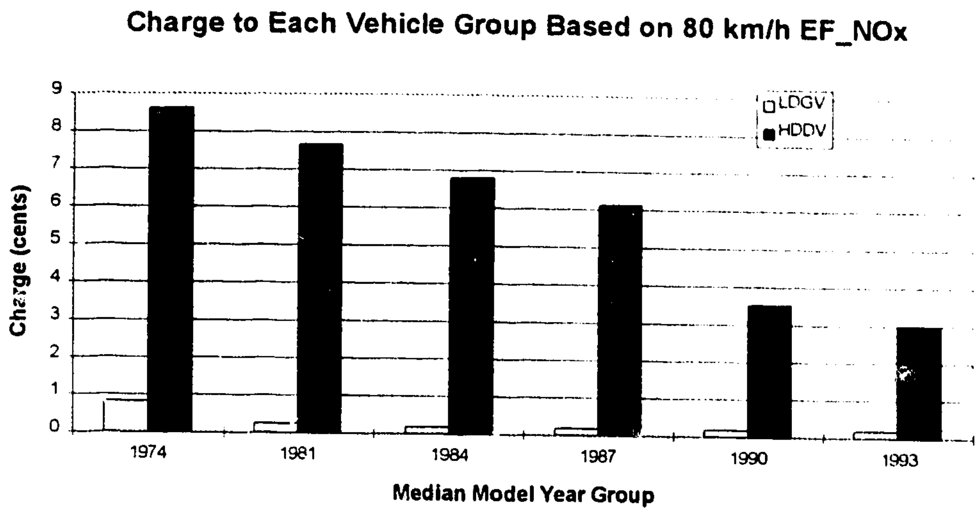

Figure 5-36. Charge Allocated Based on NO_x Emissions (80 km/h)

Speed appears to have an affect on the magnitude of the charges for each of the three pollutants, but not on the pattern of allocation between model year groups.

Figures 5-37 and 5-38 illustrate the affect of speed on the charges to a specific vehicle group, the [illegible] model year group LDGV.

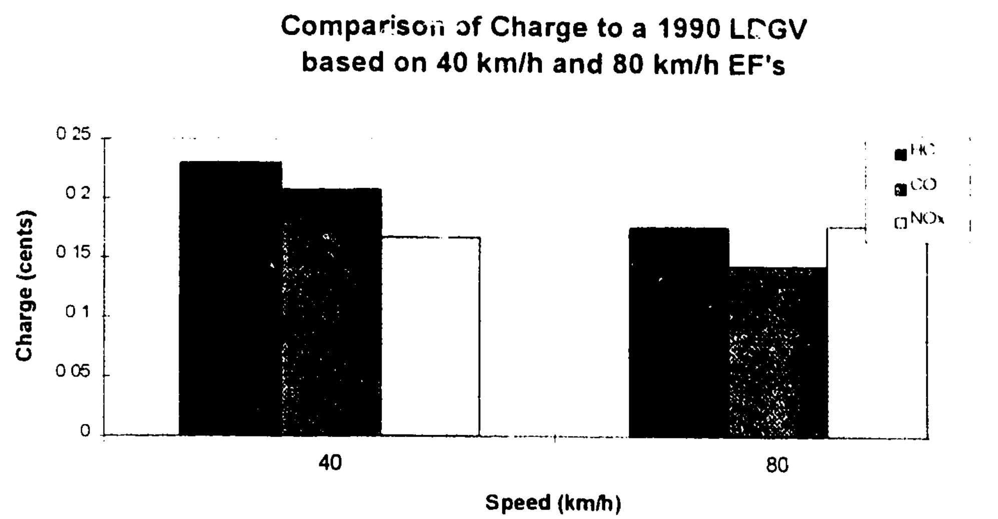

Figure 5-37. Comparison of Charges to LDGV Based on Different Speeds

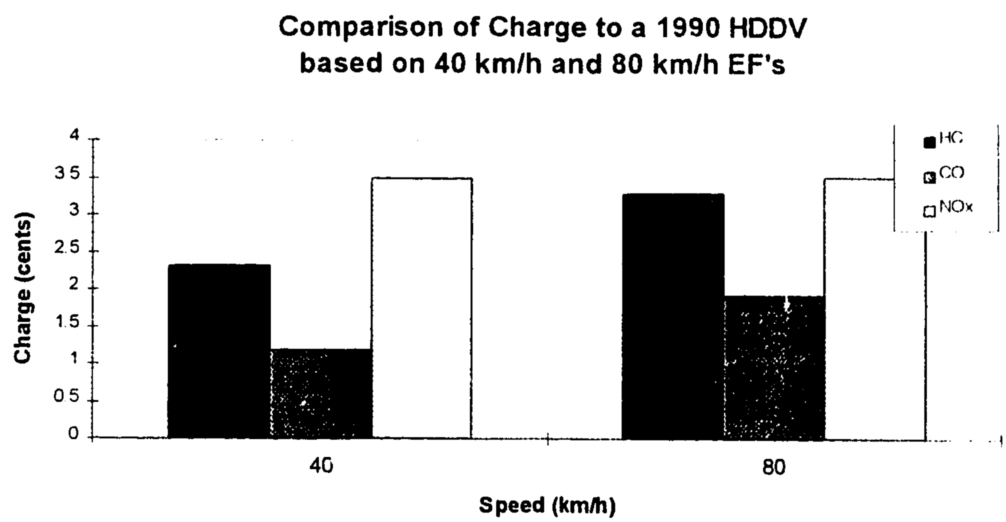

Figure 5-38. Comparison of Charges to HDDV Based on Different Speeds

Notice that in Figure 5-37, charges based on both HC and CO decrease between 40 and 80 km/h, while charges based on NO_x increase slightly. For HDDV, as shown in Figure 5-38, charges based on all three pollutants increase between 40 and 80 km/h.

In other words, an increase in the speed of the road results in an increase in the charge allocated to HDDV.

In the charts previously presented, the volume of HDDV's on the road was assumed to be 10% of the total peak hour flow of 5000 vehicles. The following charts display the results of a sensitivity analysis of the percentage of HDDV in the flow. Figure 5-39 shows the affect of the percentage of heavy trucks in the flow on the charge to a 1990 model year LDGV.

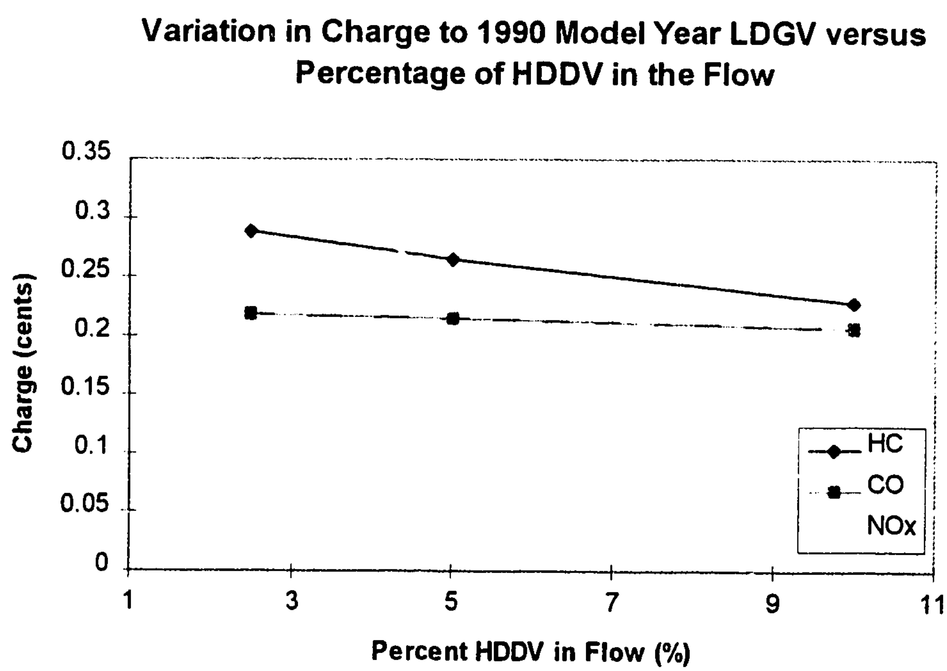

Figure 5-39. Effect of Percentage of Heavy-Duty Vehicles on LDGV Charges

A charge based on CO emissions does not change appreciably between 2.5%, 5% and 10% percent heavy trucks. A charge based on HC emissions decreases slightly as the percentage increases, from 0.29 to 0.25 cents, and a charge based on NO_x decreases significantly, from 0.33 to 0.20 cents. Likewise, for the 1990 model year HDDV, as shown in Figure 5-40, the char based on HC barely changes, that based on CO changes slightly, from 2.9 to 2.5 cents, and that based on NO_x decreases from 6.9 to 3.9 cents.

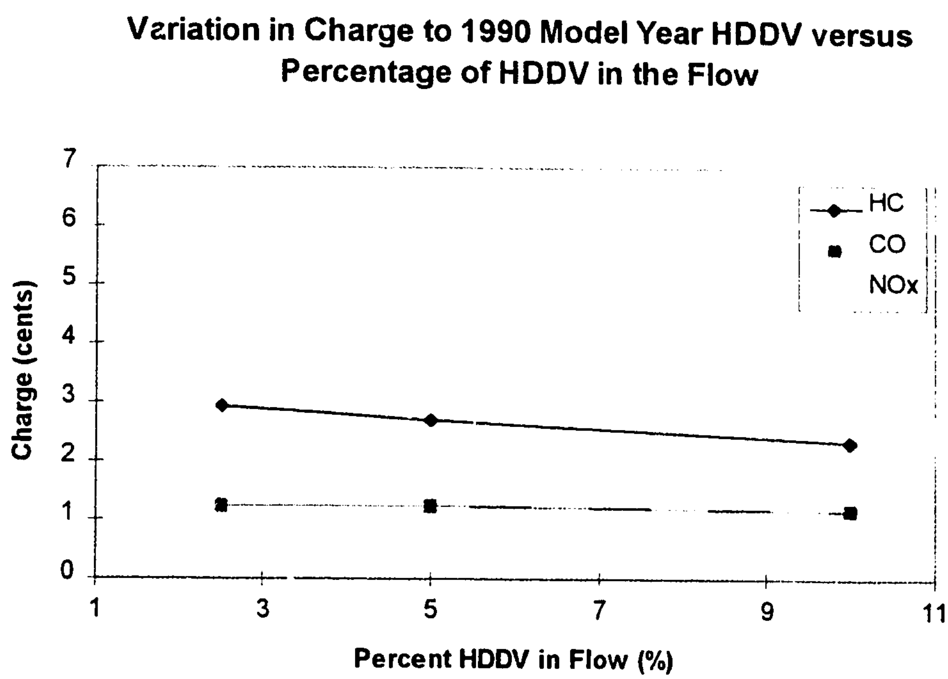

Figure 5-40. Effect of Percentage of Heavy-Duty Vehicles on HDDV Charges

In effect, the higher the number of heavy vehicles in the flow, the lower the charges will be to each vehicle class.

5.4 Concluding Remarks

The impact of charges allocated in this manner depends highly on the magnitude of the total cost of air pollution. Some conclusions can be drawn from this example, regardless of the overall magnitude of costs. The MOBILE5a model permits the determination of specific EF_p's for different model year groups, different mileage accumulations, and different speeds within each vehicle class. However, as discussed in Sections 5.1 and 5.2 of this chapter, the MOBILE model aggregates a great deal of variation within the categories of model year, mileage and so on. For instance, the amount of a given pollutant emitted from a 1986 vehicle depends as much on the quality with which it was manufactured and the maintenance that it is given by its owner as it does on the mileage accumulated or the year it was built. For this reason, it may be appropriate to determine EF_p's using a combination of prediction model results and vehicle-specific data from inspection stations or remote sensing devices, instruments that can "read" emissions from a passing vehicle. This would appear necessary to establish equitable allocation within vehicle classes; evaluating the worth of such an expense is another task altogether.

The allocation of air quality costs represents an excellent example of an equity issue in the implementation of a road pricing program, as discussed in Chapter 3. Owners of vehicles made prior to 1981 have a disincentive to drive based on this allocation structure. Charges to the model year group represented by the 1974 model year are often 10 times the charges to vehicles made in the 1980's and later. Generally speaking, owners of LDGV in this model year group would be in a lower income group that owners of later model year vehicles. Charging these owners on the basis of their vehicles' HC, CO and NO_x emissions adheres to formal equity. Demands for distributional equity, however, require that some compensation be made to these owners, who are inadvertently burdened with proportionally higher charges than other income groups.

In Sections 5.1 and 5.2 of this chapter, the effect of vehicle operating parameters on emissions was discussed. There is no way to determine the EF_p between a road that features a great deal of stop-and-go traffic and one that is flowing freely using the MOBILE model. The speed correction factor approach used in the MOBILE model would yield the same EF_p estimates for a freely flowing arterial with an average speed of 40 km/h as a congested freeway with a great deal of stop-and-go traffic and the same average speed of 40 km/h. Theory and actual measurements suggest that emissions are higher in the latter case, particularly for vehicles with faulty or poorly maintained emissions control systems (Washington, 1994). The inability to calculate EF_p's on the basis of vehicle operation is a temporary obstacle, as modal emission models are being developed and should be released within the next three years.

As in the case of noise emissions, heavy trucks bear the costs of air pollution more than automobiles. Combined with the noise charges evaluated in Chapter 4, the costs of urban goods movement would rise significantly. If road pricing were introduced in this manner, changes in the way goods are moved or priced can be expected. Concerns about the added costs imposed by urban road pricing can be expected from commuters, but the greatest opposition may be voiced by heavy vehicle operators.

Chapter 6

Conclusions and Recommendations

6.0 Overview

The preceding chapters have shown that an equitable measure of responsibility for use in urban road pricing can be derived from existing noise and air pollution prediction models. Chapter 2 argues that equitable road pricing is a viable means of attending to the costs of noise, air pollution, and congestion in urban areas. Chapter 3 presents a review of the literature in five areas: road pricing, equity in road pricing and cost allocation, motor vehicle noise pollution, motor vehicle air pollution, and assessing the costs of air and noise pollution. The significant findings of this review are that measures of responsibility for noise and air pollution should be determined for use in assessing charges to road users, and that noise and air pollution prediction models are available from which such measures can be calculated. Chapter 4 investigates the parameters of motor vehicle noise generation and propagation. Equivalency Factors for Noise, or EF_N, are derived from ten empirical prediction models. In Chapter 5, the generation of air pollution and its prediction is investigated. Equivalency Factors for Air Pollutants, or EF_p's, are derived for HC, CO and NOx using the MOBILE5 emission model. A sample problem is used to illustrate the use of the equivalency factors in road pricing schemes in each of Chapters 4 and 5.

6.1 Conclusions

6.1.1 Road Pricing

In Chapter 2, road pricing is demonstrated to be an attractive method of attending to the problems of noise, air pollution and congestion in urban areas. Road pricing is shown to fit in the category of Direct Demand Management approaches to congestion mitigation. Road pricing permits the application of average cost pricing in funding transportation construction, operations and maintenance, and is shown to be linked directly to the decisions travellers make in urban areas.

In Chapter 3, it is demonstrated that road pricing is feasible if attention is paid to the equitable allocation of costs. ITS innovations have advanced to the point that there are no technological barriers to the implementation of road pricing. Charges can be equitably allocated among road users responsible for noise and air pollution using engineering and economic principles. However, finding acceptable measures of the overall costs of noise and air pollution may be a major obstacle to the full implementation of road pricing.

In Chapters 4 and 5, a hypothetical scenario demonstrates that different vehicles can be assessed charges based on their relative contribution to overall noise and air pollution levels using the parameters of empirical engineering models.

6.1.2 Equitable Cost Allocation in Road Pricing

In Chapter 3, noise and air pollution costs are shown to be Joint Costs for which different vehicle classes are responsible to varying degrees. These costs can be allocated based on the principle of Occasioned Cost equity. Thus, road user charges can be based on measures of responsibility for noise and air pollution derived from engineering models.

6.1.3 Noise Pollution and Equivalency Factors for Noise

Traffic noise is predicted using empirical models that include variables describing both the generation of noise and the propagation of noise between the vehicle and a receiver. The models can be categorized as either low speed, interrupted flow models or high speed, uninterrupted flow models. The STAMINA model is the most widely used method of prediction in North America. The variables that have the greatest impact on the level of noise generated by traffic are the average speed of traffic, the flow rate, and the composition of the traffic stream.

The EF_N's derived from the ten prediction models vary widely due to model design, calibration dates and locations, but heavy trucks are shown to bear between 6 and 66 times as much responsibility for noise as automobiles. The EF_N for heavy and medium trucks is shown to decrease as the average speed of the traffic stream increases.

6.1.4 Air Quality and Equivalency Factors for Air Pollutants

The prediction of air pollutant emissions from motor vehicles is shown to be very complex. Many factors, including the environment, vehicle design, vehicle operation, vehicle age and maintenance, and fuel determine the amount of HC, CO, NOx and other pollutants emitted from a vehicle. The MOBILE emission model is the most widely used prediction model in North America. The MOBILE model has limited potential for deriving equivalency factors: vehicle operation is one of the strongest determinants of emission levels, and the MOBILE model is incapable of predicting emissions on the basis of operation parameters.

Nevertheless, the derivation of EF_p's from the model results in numerous significant findings. Vehicles built before 1980 are shown to be far more responsible for HC, CO and NOx pollution levels than those built since 1980. As well, the EF_p's are shown to decrease with speed. In other words, vehicles travelling at slower speeds contribute more to pollution levels than vehicles travelling at higher speeds, all else equal. As in the case of noise pollution, heavy vehicles are shown to be responsible for air pollution to a greater degree than automobiles. Assessing high charges to heavy vehicle operators would have broad economic impacts. There are many concerns not addressed in this thesis regarding such drastic changes in the cost of moving consumer goods.

6.2 Recommendations

Future research should attend to the following:

1. Modal emission models will be completed within the turn of the century. The emission algorithms being developed for these models would be invaluable as a tool

for determining EF_p's as a function of vehicle operation parameters such as acceleration and engine loads.

2. The costs to be absorbed by heavy vehicle operators are potentially very high. The trucking industry would potentially feel the greatest impact of a road pricing scheme. A logical follow-up to this study would be to analyze trends in the costs of urban goods movement and the changes that noise and air pollution charges might bring about. This would entail the incorporation of road user charges into the cost functions within transportation planning models.

3. A similar study might investigate urban household and individual trip-making. As discussed in Chapter 2, travel decisions would be affected by the charges proposed in this thesis. Travel demand models that can account for the dynamic tolls assessed to different vehicle classes on various routes would be needed to evaluate the potential impacts of these pricing schemes in urban areas.

4. An in-depth summary of the fruitful results and failings of road pricing schemes in North America, Europe and East Asia would be very instructive to policy makers. In particular, case studies of how the public's equity concerns are addressed would be particularly beneficial. A pilot study could be initiated to further analyze the implementation issues and advantages of the use of marginal cost pricing versus average cost pricing in road pricing schemes.

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Appendix A

Glossary of Terms

Sustainable Development Development that meets the needs of the present without compromising the ability of future generations to meet their own needs

Accessibility The ease with which a desired destination can be reached

Mobility The ability to move through the road network

ITS Intelligent Transportation Systems

AVI Automatic Vehicle Identification

ETC Electronic Toll Collection

Infrastructure Physical elements of the transportation system

Direct Demand Management A category of policies designed to reduce the demand for single-occupant vehicle travel on urban road networks by changing the costs perceived by vehicle operators

Volume The number of people or vehicles passing a point on a roadway in a fixed time period

Capacity The maximum rate of flow of vehicles that a roadway can accommodate under given conditions

Volume to Capacity Ratio A rough measure of a roadway's congestion

CAAA Clean Air Act Amendments of 1990

ISTEA Intermodal Surface Transportation Efficiency Act of 1991

External Costs/Externalities The effects of drivers' decisions which impact the satisfaction of others without compensation

Formal Equity The equal treatment of people within a reference group

Completeness A requirement that the costs of building and operating a road must be totally financed by the users of the road

Marginality A requirement that the costs allocated to a vehicle class are sufficiently high to cover the marginal costs occasioned by the class

Occasioned Cost Equity Costs are assigned in proportion to the costs induced or occasioned by each person

Jointly Occasioned Costs Costs that can be attributed to more than one vehicle class to varying degrees

Procedural Fairness An equity concept which entails consistency in the development of a policy

Equity in Expectations The need to maintain the conditions upon which expectations have been formed

EPA The United States Environmental Protection Agency

EF_N Equivalency factor for noise

EF_p Equivalency factor for air pollution

EF_HC Equivalency factor for hydrocarbon emissions

EF_CO Equivalency factor for carbon monoxide emissions

EF_NOx Equivalency factor for nitrogen oxide emissions

L_{eq} Equivalent Sound Units, an average of noise levels over a specified period of time

L_{10} Mean Sound Interval, the mean sound level exceeded n percent of the time

LDGV Light-duty gasoline-fueled vehicles (passenger cars)

LDGT1 Light-duty gasoline-fueled trucks up to 6000 lbs. gross vehicle weight (light pickups and vans)

LDGT2 Light-duty gasoline-fueled trucks over 6000 lbs., and up to 8500 lbs. gross vehicle weight (heavier pick-up trucks and vans, and many commercial trucks)

HDGV Heavy-duty gasoline-fueled vehicles over 8500 lbs. gross vehicle weight (heavier commercial trucks, including highway hauling trucks)

LDDV Light-duty diesel-fueled vehicles (passenger cars)

LDDT Light-duty diesel-fueled trucks up to 8500 lbs. gross vehicle weight (pickups, vans and many commercial trucks)

HDDV Heavy-duty diesel-fueled vehicles over 8500 lbs. gross vehicle weight (heavier commercial trucks, including highway hauling trucks)

MC motorcycles

US Units

mi miles, 1 mile = 1.609 kilometres

mph miles per hour, 1 mile per hour = 1.609 kilometres per hour

mph/s miles per hour per second, 1 mile per hour per second = 1.609 kilometres per hour per second

g/mi grams per mile, a measure of emissions, 1 gram per mile = 0.621 grams per kilometre

Appendix B

MOBILE5 Basic Emission Rates

```
BLOCK DATA BD03
C
C BLOCK DATA Subprogram 03: /BASEQ2/,/BASEQ4/,/BASEQ6/
C
C BLOCK DATA 03 defines the model year groups (by their upper bounds) and
C associated parameters used to select and index the intercept and slope
C arrays for the basic FTP Emission Rate (ER) equations.
C
C Common block array subscripts:
C
C BERNEW(3,100)      - BERNEW ( IBER, IFAC )
C MYGERB(25,3,8,2)   - MYGERB ( IG,      IP, IV, IR )
C MYGERU(12,2,3,8,2) - MYGERU ( JG, IFL, IP, IV, IR )
C NEWFIT(100)        - NEWFIT ( IFAC )
C NEWPAR(5,100)      - NEWPAR ( IPAR, IFAC )
C NUMERU(3,8,2)      - NUMERU ( IP, IV, IR )
C
C Common block dictionary:
C
C Name   Type    Description
C ------ ---- -------------------------------------------
C /BASEQ2/:
C
C MYGERB  I   myg upper bounds for Block Data hardcoded FTP emission rate
C             equation intercept & (LDGV <50K) slope arrays (ERBZML, ERBDR)
C MAXERB  I   maximum number of BD hardcoded ER equations possible for any
C             given combination of IP, IV and IR. MAXERB is the limit of
C             the myg dimension of arrays ERBZML, ERBDR and MYGERB.
C
C /BASEQ4/:
C
C NEWPAR  R   parameters identifying where (region, vehicle type and
C             pollutant) and when (first & last model years included)
C             to use new (user supplied) emission rates
C BERNEW  R   intercept and slopes of user supplied emission rates
C NEWFIT  I   whether or not (1 or 0) user supplied emission rate
C             information can be fit into the affected data arrays
C             (no => the new rate is not stored & not used)
C NEWCT   I   count of number of sets of new emission rate specifications
```

```
C           entered by user (not necessarily the number actually used -
C           see NEWFIT)
C  MAXCT   I   maximum number of sets allowed by NEWFLG = sets dimension of
C           the arrays of /BASEQ4/
C
C  /BASEQ6/:
C
C  MYGERU  I   myg lower & upper bounds for User supplied FTP emission rate
C           equation intercept and slopes arrays (ERUZML, ERUDR, ERU50K)
C  MAXERU  I   maximum number of user supplied ER equation parameters sets
C           allowed for each IP x IV x IR case (same limit for each case)
C  NUMERU  I   number of user supplied ER records successfully stored for
C           each IP x IV x IR case.
C  KEYER   I   key to which intercept and slope arrays pair (triple, if LDGV
C           81+ HC or CO) to use in the ER equation calculation in BEF's
C           current IP x IV x IR case:
C           1 = (ERBZML, ERBDR & ERB50K)  2 = (ERUZML, ERUDR &
ERU50K)
C  IGER    I   myg index into the ER intercept and slope arrays selected by
C           KEYER.  KEYER & IGER are set and returned by IERPTR.
C
C  Local array subscripts:
C
C  IERLO<IV>(25,3)  - IERLO<IV> ( IG, IP )
C  IERHI<IV>(25,3)  - IERHI<IV> ( IG, IP )
C
C  Local array dictionary:
C
C  Name      Type            Descriptions
C  --------- ---- -------------------------------------------------
C  IERLO<IV>  I   low altitude myg upper bounds for hardcoded FTP ERs
C  IERHI<IV>  I   high altitude myg upper bounds for hardcoded FTP ERs
C
C  Notes:
C
C  None.
C
C
      COMMON /BASEQ2/ MYGERB(25,3,8,2),MAXERB
      COMMON
/BASEQ4/NEWPAR(5,100),BERNEW(3,100),NEWFIT(100),NEWCT,MAXCT
      COMMON /BASEQ6/
MYGERU(12,2,3,8,2),MAXERU,NUMERU(3,8,2),KEYER,IGER
C
       DIMENSION
```

```
     * IERLO1(25,3),
     * IERLO2(25,3),
     * IERLO3(25,3),
     * IERLO4(25,3),
     * IERLO5(25,3),
     * IERLO6(25,3),
     * IERLO7(25,3),
     * IERLO8(25,3)
C
      EQUIVALENCE
     * (MYGERB(1,1,1,1),IERLO1(1,1)),
     * (MYGERB(1,1,2,1),IERLO2(1,1)),
     * (MYGERB(1,1,3,1),IERLO3(1,1)),
     * (MYGERB(1,1,4,1),IERLO4(1,1)),
     * (MYGERB(1,1,5,1),IERLO5(1,1)),
     * (MYGERB(1,1,6,1),IERLO6(1,1)),
     * (MYGERB(1,1,7,1),IERLO7(1,1)),
     * (MYGERB(1,1,8,1),IERLO8(1,1))
C
      DIMENSION
     * IERHI1(25,3),
     * IERHI2(25,3),
     * IERHI3(25,3),
     * IERHI4(25,3),
     * IERHI5(25,3),
     * IERHI6(25,3),
     * IERHI7(25,3),
     * IERHI8(25,3)
C
      EQUIVALENCE
     * (MYGERB(1,1,1,2),IERHI1(1,1)),
     * (MYGERB(1,1,2,2),IERHI2(1,1)),
     * (MYGERB(1,1,3,2),IERHI3(1,1)),
     * (MYGERB(1,1,4,2),IERHI4(1,1)),
     * (MYGERB(1,1,5,2),IERHI5(1,1)),
     * (MYGERB(1,1,6,2),IERHI6(1,1)),
     * (MYGERB(1,1,7,2),IERHI7(1,1)),
     * (MYGERB(1,1,8,2),IERHI8(1,1))
C
C
C /BASEQ2/:
C
C
C Continuation line code is the pollutant type:
C
```

```
C    H = HC   C = CO   N = NOx
C
C  mygs for low altitude FTP emission rates
C
C    LDGV
     DATA IERLO1/
   H  1967,1969,1971,1974,1979,1980,1981,1982,1983,1984,
   H  1985,1986,1987,1988,1989,1990,1991,1993,1994,1995,
   H  1996,1997,2020,0000,0000,
   C  1967,1969,1971,1974,1979,1980,1981,1982,1983,1984,
   C  1985,1986,1987,1988,1989,1990,1991,2020,0000,0000,
   C  0000,0000,0000,0000,0000,
   N  1967,1972,1974,1976,1979,1980,1981,1982,1983,1984,
   N  1985,1986,1987,1988,1989,1990,1991,1993,1994,1995,
   N  2020,0000,0000,0000,0000/
C    LDGT1
     DATA IERLO2/
   H  1967,1969,1971,1974,1978,1980,1983,1984,1985,1986,
   H  1987,1988,1989,1990,1991,1992,1993,1994,1995,1996,
   H  1997,2020,0000,0000,0000,
   C  1967,1969,1971,1974,1978,1980,1983,1984,1985,1986,
   C  1987,1988,1989,1990,1991,1992,1993,1994,1995,1996,
   C  1997,2020,0000,0000,0000,
   N  1967,1972,1974,1978,1980,1983,1984,1985,1986,1987,
   N  1988,1989,1990,1991,1992,1993,1994,1995,1996,1997,
   N  2020,0000,0000,0000,0000/
C    LDGT2
     DATA IERLO3/
   H  1969,1973,1978,1980,1983,1984,1985,1986,1987,1988,
   H  1989,1990,1991,1992,1993,1994,1995,1996,1997,1998,
   H  2020,0000,0000,0000,0000,
   C  1969,1973,1978,1980,1983,1984,1985,1986,1987,1988,
   C  1989,1990,1991,1992,1993,1994,1995,1996,1997,1998,
   C  2020,0000,0000,0000,0000,
   N  1969,1973,1978,1980,1983,1984,1985,1986,1987,1988,
   N  1989,1990,1991,1992,1993,1994,1995,1996,1997,1998,
   N  2020,0000,0000,0000,0000/
C
C    HDGV  M5v3
     DATA IERLO4/
   H  1962,1969,1973,1974,1975,1976,1978,1979,1980,1983,
   H  1984,1985,1986,1989,1990,1997,2000,2020,0000,0000,
   H  0000,0000,0000,0000,0000,
   C  1962,1969,1973,1974,1975,1976,1978,1979,1980,1983,
   C  1984,1985,1986,1989,1990,1997,2000,2020,0000,0000,
```

```
     C 0000,0000,0000,0000,0000,
     N 1962,1969,1973,1974,1975,1976,1978,1979,1980,1983,
     N 1984,1985,1986,1989,1990,1997,2000,2020,0000,0000,
     N 0000,0000,0000,0000,0000/
C
      DATA IERLO5/
     H 1974,1976,1977,1978,1979,2020,0000,0000,0000,0000,
     H 0000,0000,0000,0000,0000,0000,0000,0000,0000,0000,
     H 0000,0000,0000,0000,0000,
     C 1974,1976,1977,1978,1979,2020,0000,0000,0000,0000,
     C 0000,0000,0000,0000,0000,0000,0000,0000,0000,0000,
     C 0000,0000,0000,0000,0000,
     N 1974,1976,1977,1978,1979,1980,1984,2020,0000,0000,
     N 0000,0000,0000,0000,0000,0000,0000,0000,0000,0000,
     N 0000,0000,0000,0000,0000/
C
      DATA IERLO6/
     H 1977,1980,2020,0000,0000,0000,0000,0000,0000,0000,
     H 0000,0000,0000,0000,0000,0000,0000,0000,0000,0000,
     H 0000,0000,0000,0000,0000,
     C 1977,1980,2020,0000,0000,0000,0000,0000,0000,0000,
     C 0000,0000,0000,0000,0000,0000,0000,0000,0000,0000,
     C 0000,0000,0000,0000,0000,
     N 1977,1980,1987,1989,2020,0000,0000,0000,0000,0000,
     N 0000,0000,0000,0000,0000,0000,0000,0000,0000,0000,
     N 0000,0000,0000,0000,0000/
C
      DATA IERLO7/
C      HDDT
     H 1966,1968,1969,1970,1973,1976,1977,1978,1979,1981,
     H 1982,1983,1984,1985,1986,1987,1989,1990,1997,2000,
     H 2020,0000,0000,0000,0000,
     C 1966,1968,1969,1970,1973,1976,1977,1978,1979,1981,
     C 1982,1983,1984,1985,1986,1987,1989,1990,1997,2000,
     C 2020,0000,0000,0000,0000,
     N 1966,1968,1969,1970,1973,1976,1977,1978,1979,1981,
     N 1982,1983,1984,1985,1986,1987,1989,1990,1997,2000,
     N 2020,0000,0000,0000,0000/
C
      DATA IERLO8/
     H 1977,1979,1981,1984,1987,2020,0000,0000,0000,0000,
     H 0000,0000,0000,0000,0000,0000,0000,0000,0000,0000,
     H 0000,0000,0000,0000,0000,
     C 1977,1979,1981,2020,0000,0000,0000,0000,0000,0000,
     C 0000,0000,0000,0000,0000,0000,0000,0000,0000,0000,
```

```
     C 0000,0000,0000,0000,0000,
     N 1977,1979,2020,0000,0000,0000,0000,0000,0000,0000,
     N 0000,0000,0000,0000,0000,0000,0000,0000,0000,0000,
     N 0000,0000,0000,0000,0000/
C
C mygs for high altitude FTP emission rates
C
      DATA IERHI1/
     H 1967,1969,1971,1974,1976,1977,1979,1980,1981,1982,
     H 1983,1984,1985,1986,1987,1988,1989,1990,1991,1993,
     H 1994,1995,1996,1997,2020,
     C 1967,1969,1971,1974,1976,1977,1979,1980,1981,1982,
     C 1983,1984,1985,1986,1987,1988,1989,1990,1991,2020,
     C 0000,0000,0000,0000,0000,
     N 1967,1972,1974,1976,1977,1979,1980,1981,1982,1983,
     N 1984,1985,1986,1987,1988,1989,1990,1991,1993,1994,
     N 1995,2020,0000,0000,0000/
C   LDGT1
      DATA IERHI2/
     H 1967,1969,1971,1974,1976,1977,1978,1980,1981,1983,
     H 1984,1985,1986,1987,1988,1989,1990,1991,1993,1994,
     H 1995,1996,1997,2020,0000,
     C 1967,1969,1971,1974,1976,1977,1978,1980,1981,1983,
     C 1984,1985,1986,1987,1988,1989,1990,1991,1993,1994,
     C 1995,1996,1997,2020,0000,
     N 1967,1972,1974,1976,1977,1978,1980,1981,1983,1984,
     N 1985,1986,1987,1988,1989,1990,1991,1993,1994,1995,
     N 1996,1997,2020,0000,0000/
C   LDGT2
      DATA IERHI3/
     H 1969,1973,1978,1980,1981,1983,1984,1985,1986,1987,
     H 1988,1989,1990,1991,1993,1994,1995,1996,1997,1998,
     H 2020,0000,0000,0000,0000,
     C 1969,1973,1978,1980,1981,1983,1984,1985,1986,1987,
     C 1988,1989,1990,1991,1993,1994,1995,1996,1997,1998,
     C 2020,0000,0000,0000,0000,
     N 1969,1973,1978,1980,1981,1983,1984,1985,1986,1987,
     N 1988,1989,1990,1991,1993,1994,1995,1996,1997,1998,
     N 2020,0000,0000,0000,0000/
C
C   HDGV  M5v3
     DATA IERHI4/
     H 1962,1969,1973,1974,1975,1976,1978,1979,1980,1983,
     H 1984,1985,1986,1989,1990,1997,2000,2020,0000,0000,
     H 0000,0000,0000,0000,0000,
```

```
     C  1962,1969,1973,1974,1975,1976,1978,1979,1980,1983,
     C  1984,1985,1986,1989,1990,1997,2000,2020,0000,0000,
     C  0000,0000,0000,0000,0000,
     N  1962,1969,1973,1974,1975,1976,1978,1979,1980,1983,
     N  1984,1985,1986,1989,1990,1997,2000,2020,0000,0000,
     N  0000,0000,0000,0000,0000/
C
      DATA IERHI5/
     H  1974,1976,1977,1978,1979,1981,1983,2020,0000,0000,
     H  0000,0000,0000,0000,0000,0000,0000,0000,0000,0000,
     H  0000,0000,0000,0000,0000,
     C  1974,1976,1977,1978,1979,1981,1983,2020,0000,0000,
     C  0000,0000,0000,0000,0000,0000,0000,0000,0000,0000,
     C  0000,0000,0000,0000,0000,
     N  1974,1976,1977,1978,1979,1980,1984,2020,0000,0000,
     N  0000,0000,0000,0000,0000,0000,0000,0000,0000,0000,
     N  0000,0000,0000,0000,0000/
C
      DATA IERHI6/
     H  1977,1978,1980,1983,2020,0000,0000,0000,0000,0000,
     H  0000,0000,0000,0000,0000,0000,0000,0000,0000,0000,
     H  0000,0000,0000,0000,0000,
     C  1977,1978,1980,1983,2020,0000,0000,0000,0000,0000,
     C  0000,0000,0000,0000,0000,0000,0000,0000,0000,0000,
     C  0000,0000,0000,0000,0000,
     N  1977,1978,1979,1980,1984,1987,1989,2020,0000,0000,
     N  0000,0000,0000,0000,0000,0000,0000,0000,0000,0000,
     N  0000,0000,0000,0000,0000/
C
      DATA IERHI7/
C      HDDT
     H  1966,1968,1969,1970,1973,1976,1977,1978,1979,1981,
     H  1982,1983,1984,1985,1986,1987,1989,1990,1997,2000,
     H  2020,0000,0000,0000,0000,
     C  1966,1968,1969,1970,1973,1976,1977,1978,1979,1981,
     C  1982,1983,1984,1985,1986,1987,1989,1990,1997,2000,
     C  2020,0000,0000,0000,0000,
     N  1966,1968,1969,1970,1973,1976,1977,1978,1979,1981,
     N  1982,1983,1984,1985,1986,1987,1989,1990,1997,2000,
     N  2020,0000,0000,0000,0000/
C
      DATA IERHI8/
     H  1977,1979,1981,1984,1987,2020,0000,0000,0000,0000,
     H  0000,0000,0000,0000,0000,0000,0000,0000,0000,0000,
     H  0000,0000,0000,0000,0000,
```

```
     C  1977,1979,1981,2020,0000,0000,0000,0000,0000,0000,
     C  0000,0000,0000,0000,0000,0000,0000,0000,0000,0000,
     C  0000,0000,0000,0000,0000,
     N  1977,1979,2020,0000,0000,0000,0000.0000,0000,0000,
     N  0000,0000,0000,0000,0000,0000,0000,0000,0000.0000,
     N  0000,0000,0000,0000,0000/
C
      DATA MAXERB/25/
C
C
C /BASEQ4/:
C
C
C Except for the limit on the total number of replacement ef parameter records,
C the /BASEQ4/ block is initialized to dummy zeroes, since the cells either
C get read in or assigned values or are not used.
C
     DATA NEWPAR/500*0/,BERNEW/300*0.0/,NEWFIT/100*0/,NEWCT/0/
     DATA MAXCT/100/
C
C
C /BASEQ6/:
C
C
C Initialize all user supplied myg cases to 0, to allow IERPTR storage
C algorithm to work, and NUMERU to 0, to allow storage and access algorithms
C to work.  KEYER and IGER are set as necessary by IERPTR.
C
     DATA MYGERU/1152*0/,MAXERU/12/,NUMERU/48*0/,KEYER/1/,IGER/1/
C
     END
     BLOCK DATA BD04
C
C BLOCK DATA Subprogram 04: /BASEQ1/,/BASEQ5/,/BASEQ7/
C
C
C BLOCK DATA 04 initializes the zero mile levels and deterioration rates
C (intercepts & slopes) of the base FTP exhaust emission rate equations.
C
C Common block array subscripts:
C
C
C ERBDR(25,3,8,2)  -  ERBDR  ( IGER, IP,  IV, IR )
C ERBZML(25,3,8,2)  -  ERBZML ( IGER, IP,  IV, IR )
C ERB50K(18,2,3,2)  -  ERB50K ( IG50, IP50, IV, IR )
```

```
C ERUDR(18,3,8,2)  - ERUDR  ( IGER, IP,  IV, IR )
C ERUZML(18,3,8,2) - ERUZML ( IGER, IP,  IV, IR )
C ERU50K(18,3,3,2) - ERU50K ( IG50, IP50, IV, IR )
C HDVZML(25,2)     - HDVZML ( MY,  IREJN )
C HDVBDR(25,2)     - HDVBDR ( MY,  IREJN )
C IHDVMY(25,2)     - IHDVMY ( MY,  IREJN )
C IPMOD(3)         - IPMOD  ( IP )
C
C
C Common block dictionary:
C
C  Name   Type        Description
C ------ ---- ------------------------------------------
C Note: 3rd character syntax: B = Block Data hardcoded, U = User supplied
C
C /BASEQ1/:
C
C ERBZML  R   Hardcoded FTP Emission Rate (ER) equation zero mile levels
C ERBDR   R   Hardcoded FTP ER equation deterioration rates
C ERB50K  R   Hardcoded FTP ER equation deterioration rates 81+ LDGV
C             and 91+ LDGT HC/CO
C
C /BASEQ5/:
C
C ERUZML  R   User supplied (via NEWFLG) FTP ER equation zero mile levels
C ERUDR   R   User supplied FTP ER equation deterioration rates
C ERU50K  R   User supplied FTP ER equation deterioration rates, 81+ LDGV
C
C /BASEQ7/:
C
C IPMOD   I   Flag vector: for each IP whether or not 1 or more of its
C             FTP ER equation coefficient pairs have been supplied by the
C             user.  0 = no & 1 = yes  (yes means idle ef skipped for 1 or
C             more IV means skip VIDLE(IP) calculation)
C
C /BASEQ8/:
C
C Local array subscripts:
C
C <J><K><LL>(25,3,2)  -  <J><K><LL> ( IG, IP, IVER )
C
C where <J> = D (deterioration rate), Z (zero mile level)
C       <K> = L (low altitude region), H (high altitude region)
C       <LL> = 12 (LDGV,LDGT1), 34 (LDGT2,HDGV), 56 (LDDV,LDDT), 78
(HDDV,MC)
```

```
C      IVER = 1 (1st of vt pair LL), 2 (2nd of vt pair LL)
C
C
C  Local array dictionary:
C
C   Name      Type             Descriptions
C  ---------  ----  --------------------------------------------------------
C  <J><K><LL>  R   as defined above, the slope/intercept <J> in region <K>
C                  for vehicle type pair <LL> of the FTP exhaust emission
C                  rate equation
C
C  Notes:
C
C  BD04 was modified to include kinked EFs for LDGT in MOBILE5.
C
C
C
      COMMON /BASEQ1/ ERBZML(25,3,8,2),ERBDR(25,3,8,2),ERB50K(18,3,3,2)
      COMMON /BASEQ5/ ERUZML(18,3,8,2),ERUDR(18,3,8,2),ERU50K(18,3,3,2)
      COMMON /BASEQ7/ IPMOD(3)

C
      DIMENSION ZL12(25,3,2),ZL34(25,3,2),ZL56(25,3,2),ZL78(25,3,2)
      DIMENSION ZH12(25,3,2),ZH34(25,3,2),ZH56(25,3,2),ZH78(25,3,2)
      DIMENSION DL12(25,3,2),DL34(25,3,2),DL56(25,3,2),DL78(25,3,2)
      DIMENSION DH12(25,3,2),DH34(25,3,2),DH56(25,3,2),DH78(25,3,2)
C
      DIMENSION ERB51(18,3,3),ERB52(18,3,3)
C
      EQUIVALENCE
     * (ERBZML(1,1,1,1),ZL12(1,1,1)), (ERBZML(1,1,3,1),ZL34(1,1,1)),
     * (ERBZML(1,1,5,1),ZL56(1,1,1)), (ERBZML(1,1,7,1),ZL78(1,1,1)),
     * (ERBZML(1,1,1,2),ZH12(1,1,1)), (ERBZML(1,1,3,2),ZH34(1,1,1)),
     * (ERBZML(1,1,5,2),ZH56(1,1,1)), (ERBZML(1,1,7,2),ZH78(1,1,1))
C
      EQUIVALENCE
     * (ERBDR(1,1,1,1),DL12(1,1,1)), (ERBDR(1,1,3,1),DL34(1,1,1)),
     * (ERBDR(1,1,5,1),DL56(1,1,1)), (ERBDR(1,1,7,1),DL78(1,1,1)),
     * (ERBDR(1,1,1,2),DH12(1,1,1)), (ERBDR(1,1,3,2),DH34(1,1,1)),
     * (ERBDR(1,1,5,2),DH56(1,1,1)), (ERBDR(1,1,7,2),DH78(1,1,1))
C
      EQUIVALENCE
     * (ERB50K(1,1,1,1),ERB51(1,1,1)), (ERB50K(1,1,1,2),ERB52(1,1,1))
C
C
```

```
C  Hardcoded FTP ER equation zero mile levels and deterioration (per 10000
C  miles) rates are blocked by vehicle class.  Within each block, the
C  continuation code is the pollutant type: H = HC, C = CO and N = NOx.
C  There are up to 2 lines and 20 cases per pollutant per vehicle class per
C  region per equation parameter.
C
C
C  /BASEQ1/:
C
C
C  Hardcoded zero mile exhaust levels
C
C  Low altitude region
C
      DATA ZL12/
C  LDGV
     H 7.25, 4.43, 3.00, 3.38, 1.06, 0.36,0.287,0.286,0.241,0.247,
     H0.249,0.253,0.253,0.257,0.258,0.260,0.261,0.261,0.247,0.233,
     H0.210,0.193,0.184, 2*0.,
     C78.27,56.34,42.17,40.94,17.72, 6.09,3.069,3.105,3.255,3.184,
     C2.920,2.740,2.704,2.490,2.424,2.203,2.166,2.147, 7*0.,
     N 3.44, 4.35, 2.86, 2.44, 1.79, 1.50,0.648,0.635,0.578,0.465,
     N0.469,0.425,0.442,0.483,0.478,0.464,0.465,0.467,0.365,0.240,
     N0.178, 4*0.,
C  LDGT1
     H 7.25, 4.43, 3.00, 3.36, 1.80, 0.87, 0.82, 0.70,0.408,0.392,
     H0.377,0.361,0.358,0.355,0.354,0.354,0.354,0.312,0.271,0.231,
     H0.212,0.202, 3*0.,
     C 78.27,56.34,42.17,40.78,24.55,12.28,12.58, 9.43,5.074,4.642,
     C 4.358,4.024,3.948,3.824,3.800,3.800,3.800,3.682,3.565,3.071,
     C 2.636,2.419, 3*0.,
     N  3.44, 4.35, 2.87, 2.70, 1.77, 1.64, 1.12,1.116,0.985,0.838,
     N 0.690,0.661,0.639,0.630,0.630,0.630,0.472,0.315,0.236,0.236,
     N 0.236, 4*0. /
C
      DATA ZL34/
C  LDGT2
     H 9.57, 6.28, 6.28, 0.87, 0.82, 0.70,0.408,0.392,0.377,0.361,
     H0.358,0.355,0.354,0.354,0.354,0.354,0.354,0.324,0.294,0.268,
     H0.242, 4*0.,
     C93.98,60.08,60.08,12.28,12.58, 9.43,5.074,4.642,4.358,4.024,
     C3.948,3.824,3.800,3.800,3.800,3.800,3.800,3.694,3.588,3.249,
     C2.911, 4*0.,
     N 5.44, 6.45, 4.61, 1.77, 1.64, 1.12,1.116,0.985,0.838,0.690,
     N0.661,0.639,0.630,0.630,0.630,0.630,0.630,0.550,0.470,0.422,
```

```
     N0.374, 4*0.,
C  HDGV  M5v3
     H19.72,19.31, 9.73, 9.61, 8.88, 8.41, 7.20, 3.67, 3.45, 3.27,
     H 3.26, 2.28, 2.00, 0.82, 0.82, 0.82, 0.81, 0.81, 7*0.,
     C240.22,235.25,166.26,164.30,151.70,143.73,123.05,57.18,53.77,
     C 50.91, 50.75, 35.79, 28.21, 11.17, 11.15, 11.10, 11.04, 11.03,
     C 7*0.,
     N 9.41, 9.22, 9.87, 7.11, 6.56, 6.22, 5.32, 5.95, 5.59, 5.30,
     N 5.28, 5.21, 5.20, 5.21, 4.27, 3.55, 2.82, 2.82, 7*0./
C
      DATA ZL56/
C  LDDV
     H 1.31, 0.42, 0.42, 0.42, 0.42, 0.29,19*0.,
     C 2.71, 1.17, 1.17, 1.17, 1.17, 1.15,19*0.,
     N 1.46, 1.40, 1.40, 1.40, 1.40, 1.40, 1.31, 0.87,17*0.,
C  LDDT
     H 0.86, 0.86, 0.43, 22*0.,
     C 1.97, 1.97, 1.33, 22*0.,
     N 1.83, 1.83, 1.48, 1.07,1.03,20*0./
C
      DATA ZL78/
C  HDDV
     H 3.54, 3.66, 3.78, 3.81, 3.91, 3.91, 3.99, 3.92, 3.51, 3.17,
     H 2.78, 2.66, 2.82, 2.59, 2.28, 2.23, 2.18, 2.13, 2.10, 2.10,
     H 2.10, 4*0.,
     C 10.32,10.69,11.04,11.13,11.42,11.42,11.65,11.44,14.04,12.67,
     C 11.12,10.66,11.26,10.35,10.36,10.14,9.90,9.67,9.54,9.53,
     C 9.52, 4*0.,
     N22.99,23.83,24.59,24.80,25.46,25.44,25.97,25.50,23.78,21.47,
     N18.84,18.06,19.08,17.53,17.56,17.18,16.77,9.87,8.13,6.49,
     N 6.49, 4*0.,
C  MC
     H 8.78, 2.40, 1.93, 1.65, 1.31, 1.20,19*0.,
     C33.42,24.39,17.51,17.40,21*0.,
     N 0.25, 0.68, 0.85,22*0./
C
C  High altitude region
C
      DATA ZH12/
C  LDGV
     H 9.350,5.600,4.580,4.620,2.000,0.930,2.080,0.780,0.531,0.350,
     H 0.223,0.247,0.249,0.253,0.253,0.257,0.258,0.260,0.261,0.261,
     H 0.247,0.233,0.210,0.193,0.184,
     C117.70,85.54,79.64,75.68,47.03,19.63,41.83,22.80,11.998,8.269,
     C 3.286,3.184,2.920,2.740,2.704,2.490,2.424,2.203,2.166,2.147,
```

```
     C 5*0.,
     N 1.960,2.910,1.920,1.700,1.370,0 970,0.820,0.504,0.625,0.766,
     N 0.465,0.469,0.425,0.442,0.483,0.478,0.464,0.465,0.467,0.365,
     N 0.240,0.178, 3*0.,
C LDGT1
     H 9.35, 5.60, 4.58, 4.58, 3.40, 1.60, 3.53, 1.66, 1.66, 1.07,
     H 1.05,0.509,0.490,0.471,0.451,0.447,0.444,0.442,0.442,0.312,
     H 0.271,0.231,0.212,0.202, 0.,
     C117.70,85.54,79.64,75.63,58.01,22.86,53.57,44.25,44.25,30.16,
     C 23.35,7.103,6.498,6.101,5.633,5.526,5.352,5.318,5.318,3.682,
     C 3.565,3.071,2.636,2.419, 0.,
     N 1.96, 2.91, 1.91, 1.88, 2.25, 1.88, 0.97, 0.97, 1.46, 1.22,
     N 1.116,0.985,0.838,0.690,0.661,0.639,0.630,0.630,0.472,0.315,
     N 0.236,0.236,0.236, 2*0. /
C
      DATA ZH34/
C LDGT2
     H 12.35, 8.56, 8.56, 1.66, 1.66, 1.07, 1.05,0.509,0.490,0.471,
     H 0.451,0.447,0.444,0.442,0.442,0.354,0.354,0.324,0.294,0.268,
     H 0.242, 4*0.,
     C141.35,107.72,107.72,44.249,44.25,30.16,23.35,7.103,6.498,6.101,
     C 5.633,5.526,5.352,5.318,5.318,3.800,3.800,3.694,3.588,3.249,
     C 2.911, 4*0.,
     N 3.10, 4.32, 3.07, 0.97, 0.97, 1.46, 1.22,1.116,0.985,0.838,
     N 0.690,0.661,0.639,0.630,0.630,0.630,0.630,0.550,0.470,0.422,
     N 0.374, 4*0.,
C HDGV
     H26.87,26.32,13.25,13.10,12.09,11.46, 9.81, 5.00, 4.70, 4.45,
     H 4.44, 3.12, 2.73, 1.40, 1.39, 1.39, 1.38, 1.38, 7*0.,
     C430.72,421.81,298.10,294.58,272.00,257.71,220.63,102.53,96.41,
     C91.29,90.99,64.16,50.57,30.62,30.56,30.44,30.27,30.24, 7*0.,
     N 6.27, 6.14, 6.58, 4.74, 4.37, 4.14, 3.55, 3.97, 3.73, 3.53,
     N 3.52, 3.48, 3.47, 3.47, 3.41, 2.83, 2.26, 2.25, 7*0./
C
      DATA ZH56/
C LDDV
     H 3.01, 0.97, 0.97, 0.97, 0.97, 0.67, 0.40, 0.29,17*0.,
     C 4.74, 2.05, 2.05, 2.05, 2.05, 2.01, 2.01, 1.15,17*0.,
     N 1.46, 1.40, 1.40, 1.40, 1.40, 1.40, 1.31, 0.87,17*0.,
C LDDT
     H 1.98, 1.98, 1.98, 0.99, 0.54, 20*0.,
     C 3.45, 3.45, 3.45, 3.45, 2.33, 2.33, 19*0.,
     N 1.83, 1.83, 1.83, 1.83, 1.48, 1.48, 1.07, 1.03, 17*0./
C
      DATA ZH78/
```

```
C HDDV
   H 8.13, 8.43, 8.70, 8.77, 9.01, 9.00, 9.19, 9.02, 8.07, 7.28,
   H 6.37, 6.13, 6.47, 5.95, 5.25, 5.14, 5.01, 4.90, 4.83, 4.82,
   H 4.82, 4*0.,
   C18.05,18.71,19.30,19.47,19.99,19.97,20.38,20.01,24.56,22.17,
   C19.39,18.65,19.71,18.11,18.13,17.75,17.32,16.92,16.69,16.67,
   C16.66, 4*0.,
   N22.99,23.83,24.59,24.80,25.46,25.44,25.97,25.50,23.78,21.47,
   N18.77,18.06,19.08,17.53,17.56,17.18,16.77, 9.87, 8.13, 6 49,
   N 6.49, 4*0.,
C MC
   H 11.43, 3.02, 2.95, 2.52, 2.00, 1.84, 0.00, 0.00,17*0.00,
   C 50.13, 37.07, 33.09, 32.89, 0.00, 0.00, 0.00, 0.00,17*0.00,
   N 0.14, 0.45, 0.57, 0.00, 0.00, 0.00, 0.00, 0.00,17*0.00/
C
C Hardcoded deterioration rates
C
C Low altitude region
C
    DATA DL12/
C LDGV                    - 1980 -
   H 0.18, 0.25, 0.37, 0.16, 0.28,0.205,0.101,0.105,0.089,0.073,
   H0.077,0.071,0.070,0.070,0.073,0.075,0.075,0.076,0.074,0.073,
   H0.072,0.072,0.072, 2*0.,
   C 2.25, 2.55, 3.13, 2.35, 2.46,1.958,1.663,1.727,1.549,1.193,
   C1.331,1.240,1.242,1.289,1.343,1.423,1.439,1.448, 7*0.,
   N 0.00, 0.00, 0.05, 0.04, 0.11,0.102,0.063,0.066,0.067,0.079,
   N0.078,0.082,0.078,0.077,0.080,0.082,0.082,0.083,0.083,0.083,
   N0.083, 4*0.,
C LDGT1
   H 0.18, 0.25, 0.37, 0.17, 0.27, 0.28, 0.15, 0.15,0.077,0.071,
   H0.070,0.070,0.073,0.075,0.075,0.076,0.076,0.074,0.073,0.072,
   H0.072,0.072, 3*0.,
   C 2.25, 2.55, 3.13, 2.44, 2.59, 2.43, 1.46, 1.46,1.331,1.240,
   C1.242,1.289,1.343,1.423,1.439,1.448,1.448,1.448,1.448,1.448,
   C1.448,1.448, 3*0.,
   N 0.00, 0.00, 0.04, 0.03, 0.06, 0.03, 0.07,0.078,0.082,0.078,
   N 0.077,0.08,0.082,0.082,0.083,0.083,0.083,0.083,0.083,0.083,
   N 0.083, 4*0. /
C
    DATA DL34/
C LDGT2
   H 0.18, 0.25, 0.17, 0.28, 0.15, 0.15,0.077,0.071,0.070,0.070,
   H0.073,0.075,0.075,0.076,0.076,0.074,0.073,0.072,0.072,0.072,
   H0.072, 4*0.,
```

```
     C 2.25, 2.55, 2.44, 2.43, 1.46, 1.46,1.331,1.240,1.242,1.289,
     C1.343,1.423,1.439,1.448,1.448,1.448,1.448,1.448,1.448,1.448,
     C1.448, 4*0.,
     N 0.00, 0.00, 0.04, 0.06, 0.03, 0.07,0.078,0.082,0.078,0.077,
     N 0.08,0.082,0.082,0.083,0.083,0.083,0.083,0.083,0.083,0.083,
     N0.083, 4*0.,
C HDGV
     H 0.37, 0.36, 0.39, 0.26, 0.24, 0.22, 0.19, 0.18, 0.17, 0.16,
     H 0.16, 0.05, 0.05, 0.09, 0.09, 0.09, 0.09, 0.09, 7*0.,
     C 5.76, 5.64, 7.05, 6.67, 6.16, 5.83, 4.99, 4.79, 4.51, 4.27,
     C 4.25, 0.86, 0.86, 0.64, 0.64, 0.64, 0.64, 0.64, 7*0.,
     N 0.00, 0.00, 0.00, 0.09, 0.08, 0.07, 0.06, 0.06, 0.06, 0.05,
     N 0.05, 0.03, 0.03, 0.03, 0.04, 0.04, 0.04, 0.04, 7*0./
C
      DATA DL56/
C LDDV
     H 0.08, 0.07, 0.07, 0.07, 0.07, 0.03,19*0.,
     C 0.13, 0.09, 0.09, 0.09, 0.09, 0.04,19*0.,
     N 0.04, 0.04, 0.04, 0.04, 0.04, 0.04, 0.03, 0.03,17*0.,
C LDDT
     H 0.08, 0.08, 0.04, 22*0.,
     C 0.10, 0.10, 0.04, 22*0.,
     N 0.08, 0.08, 0.03, 0.03, 0.03, 20*0./
C
      DATA DL78/
C HDDV
     H 0.06, 0.06, 0.06, 0.06, 0.06, 0.06, 0.06, 0.06, 0.00, 0.00,
     H 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 6*0.,
     C 0.14, 0.15, 0.15, 0.15, 0.16, 0.16, 0.16, 0.16, 0.12, 0.11,
     C 0.10, 0.09, 0.10, 0.09, 0.09, 0.09, 0.08, 0.08, 0.08, 0.08,
     C 0.08, 4*0.,
     N 0.17, 0.18, 0.18, 0.19, 0.19, 0.19, 0.19, 0.19, 0.00, 0.00,
     N 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 6*0.,
C MC
     H 0.75, 1.44, 1.15, 0.95, 0.75, 0.70,19*0.,
     C 3.22, 3.56, 2.53, 2.46, 21*0.,
     N 0.03, 0.00, 0.00,22*0./
C
C High altitude region
C
      DATA DH12/
C LDGV                         - 1980 -
     H 0.180,0.250,0.370,0.160,0.280,0.280,0.280,0.205,0.101,0.105,
     H 0.089,0.073,0.077,0.071,0.070,0.070,0.073,0.075,0.075,0.076,
     H 0.074,0.073,0.072,0.072,0.072,
```

```
     C 2.250,2.550,3.130,2.350,2.460,2.460,2.460,1.958,1.663,1.727,
     C 1.549,1.193,1.331,1.240,1.242,1.289,1.343,1.423,1.439,1.448,
     C  5*0.,
     N 0.000,0.000,0.050,0.040.0.110,0.110,0.102,0.063,0.066,0.067,
     N 0.079,0.078,0.082,0.078,0.077,0.080,0.082,0.082,0.083,0.083,
     N 0.083,0.083, 3*0.,
C LDGT1
     H 0.18, 0.25, 0.37, 0.17, 0.27, 0.27, 0.27, 0.28, 0.28, 0.15,
     H 0.15,0.077,0.071,0.070,0.070,0.073,0.075,0.075,0.076,0.074,
     H0.073,0.072,0.072,0.072,  0.,
     C 2.25, 2.25, 3.13, 2.44, 2.59, 2.59, 2.59, 2.43, 2.43, 1.46,
     C 1.46,1.331,1.240,1.242,1.289,1.343,1.423,1.439,1.448,1.448,
     C1.448,1.448,1.448,1.448,  0.,
     N 0.0 , 0.0 , 0.04, 0.03, 0.03, 0.03, 0.06, 0.06, 0.03, 0.07,
     N0.078,0.082,0.078,0.077,0.080,0.082,0.082,0.083,0.083,0.083,
     N0.083,0.083,0.083, 2*0. /
C
      DATA DH34/
C LDGT2
     H 0.18, 0.25, 0.17, 0.28, 0.28, 0.15, 0.15,0.077,0.071,0.070,
     H0.070,0.073,0.075,0.075,0.076,0.074,0.073,0.072,0.072,0.072,
     H0.072, 4*0.,
     C 2.25, 2.55, 2.44, 2.43, 2.43, 1.46, 1.46,1.331,1.240,1.242,
     C1.289,1.343,1.423,1.439,1.448,1.448,1.448,1.448,1.448,1.448,
     C1.448, 4*0.,
     N 0.0 , 0.0 , 0.04, 0.06, 0.06, 0.03, 0.07,0.078,0.082,0.078,
     N0.077,0.080,0.082,0.082,7*0.083, 4*0.,
C HDGV
     H 0.37, 0.36, 0.39, 0.26, 0.24, 0.22, 0.19, 0.18, 0.17, 0.16,
     H 0.16, 0.05, 0.05, 0.09, 0.09, 0.09, 0.09, 0.09, 7*0.,
     C 5.76, 5.64, 7.05, 6.67, 6.16, 5.83, 4.99, 4.79, 4.51, 4.27,
     C 4.25, 0.86, 0.86, 0.64, 0.64, 0.64, 0.64, 0.64, 7*0.,
     N 0.00, 0.00, 0.00, 0.09, 0.08, 0.07, 0.06, 0.06, 0.06, 0.05,
     N 0.05, 0.03, 0.03, 0.03, 0.04, 0.04, 0.04, 0.04, 7*0./
C
      DATA DH56/
C LDDV
     H 0.08, 0.07, 0.07, 0.07, 0.07, 0.03, 0.03, 0.03,17*0.,
     C 0.13, 0.09, 0.09, 0.09, 0.09, 0.04, 0.04, 0.04,17*0.,
     N 0.04, 0.04, 0.04, 0.04, 0.04, 0.04, 0.03, 0.03,17*0.,
C LDDT
     H 0.08, 0.08, 0.08, 0.04, 0.04, 20*0.,
     C 0.10, 0.10, 0.10, 0.10, 0.04, 0.04, 19*0.,
     N 0.06, 0.06, 0.06, 0.06, 0.03, 0.03, 0.03, 0.03, 17*0./
C
```

```
      DATA DH78/
C  HDDV
   H 0.06, 0.06, 0.06, 0.06, 0.06, 0.06, 0.06, 0.06, 0.00, 0.00,
   H 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 6*0.,
   C 0.14, 0.15, 0.15, 0.15, 0.16, 0.16, 0.16, 0.16, 0.12, 0.11,
   C 0.09, 0.09, 0.10, 0.09, 0.09, 0.09, 0.08, 0.08, 0.08, 0.08,
   C 0.08, 4*0.,
   N 0.17, 0.18, 0.18, 0.19, 0.19, 0.19, 0.19, 0.19, 0.00, 0.00,
   N 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 6*0.,
C  MC
   H 0.75, 1.44, 1.15, 0.95, 0.75, 0.70, 0.00, 0.00, 0.00,16*0.,
   C 3.22, 3.56, 2.53, 2.46, 0.00, 0.00, 0.00, 0.00, 0.00,16*0.,
   N 0.03, 0.0 , 0.0 , 0.00, 0.00, 0.00, 0.00, 0.00, 0.00,16*0./
C
C  Hardcoded 50,000+ mile deterioration rates for LDGT and LDGT1/2.
C  LDGT1/2 rates are for MY 1991+ only.
C
C  Low altitude
C
      DATA ERB51/
C  LDGV
   H0.285,0.271,0.274,0.282,0.284,0.282,0.271,0.265,0.277,0.280,
   H0.281,0.283,0.283,0.279,0.275, 3*0.273,
   C3.609,3.318,3.345,3.604,3.547,3.554,3.403,3.286,3.423,3.407,
   C3.419,3.434, 6*3.434,
   N0.190,0.190,0.199,0.224,0.210,0.214,0.213,0.204,0.198,0.189,
   N0.188,0.186,0.186,0.189,0.193, 3*0.195,
C  LDGT1
   H0.150,0.150,0.150,0.150,0.284,0.282,0.271,0.265,0.277,0.280,
   H0.281,0.283,0.283,0.279,0.275,0.273,0.273,0.273,
   C1.460,1.460,1.460,1.460,3.547,3.554,3.403,3.286,3.423,3.407,
   C3.419,3.434,3.434,3.434,3.434,3.434,3.434,3.434,
   N0.030,0.030,0.030,0.070,0.210,0.214,0.213,0.204,0.198,0.189,
   N0.188,0.186,0.186,0.186,0.186,0.186,0.186,0.186,
C  LDGT2
   H0.150,0.150,0.150,0.150,0.284,0.282,0.271,0.265,0.277,0.280,
   H0.281,0.283,0.283,0.279,0.275,0.273,0.273,0.273,
   C1.460,1.460,1.460,1.460,3.547,3.554,3.403,3.286,3.423,3.407,
   C3.419,3.434,3.434,3.434,3.434,3.434,3.434,3.434,
   N0.030,0.030,0.030,0.070,0.210,0.214,0.213,0.204,0.198,0.189,
   N0.188,0.186,0.186,0.186,0.186,0.186,0.186,0.186 /
C
C  High altitude
C
      DATA ERB52/
```

```
C LDGV
     H0.285,0.271,0.274,0.282,0.284,0.282,0.271,0.265,0.277,0.280,
     H0.281,0.283,0.283,0.279,0.275, 3*0.273,
     C3.609,3.318,3.345,3.604,3.547,3.554,3.403,3.286,3.423,3.407,
     C3.419,3.434, 6*3.434,
     N0.190,0.190,0.199,0.224,0.210,0.214,0.213,0.204,0.198,0.189,
     N0.188,0.186,0.186,0.189,0.193, 3*0.195,
C LDGT1
     H0.150,0.150,0.150,0.150,0.284,0.282,0.271,0.265,0.277,0.280,
     H0.281,0.283,0.283,0.279,0.275,0.273,0.273,0.273,
     C1.460,1.460,1.460,1.460,3.547,3.554,3.403,3.286,3.423,3.407,
     C3.419,3.434,3.434,3.434,3.434,3.434,3.434,3.434,
     N0.030,0.030,0.030,0.070,0.210,0.214,0.213,0.204,0.198,0.189,
     N0.188,0.186,0.186,0.186,0.186,0.186,0.186,0.186,
C LDGT2
     H0.150,0.150,0.150,0.150,0.284,0.282,0.271,0.265,0.277,0.280,
     H0.281,0.283,0.283,0.279,0.275,0.273,0.273,0.273,
     C1.460,1.460,1.460,1.460,3.547,3.554,3.403,3.286,3.423,3.407,
     C3.419,3.434,3.434,3.434,3.434,3.434,3.434,3.434,
     N0.030,0.030,0.030,0.070,0.210,0.214,0.213,0.204,0.198,0.189,
     N0.188,0.186,0.186,0.186,0.186,0.186,0.186,0.186 /
C
C /BASEQ5/:
C
C
C User supplied zero mile levels and deterioration rates arrays are
C initialized to all zeroes.
C
      DATA ERUZML/864*0.0/,ERUDR/864*0.0/,ERU50K/324*0.0/
C
C
C /BASEQ7/:
C
C
C IPMOD starts all zeroes ( = all "no mods" ).
C
      DATA IPMOD/3*0/
C
C
     END
```

Appendix C

MOBILE5 Speed Correction Factors

```
C BLOCK DATA Subprogram 01: /SPEED1/
C
C BLOCK DATA 01 defines and initializes the speed correction factor (scf)
C coefficients for vehicle types LDGV, LDGT1/2 and MC.
C
C Common block array subscripts:
C
C SK1(6,21,3)   - SK1 ( ICOEF5, ISP, IP )
C SH(6,21)      - SH ( ICOEF5, ISP )
C SC(6,21)      - SC ( ICOEF5, ISP )
C SN(6,21)      - SN ( ICOEF5, ISP )
C SKG(2,6,2)    - SKG ( IS2C, ISP, IPG )
C SK2C(2,14,3,3) - SK2C ( IS2C, ISP, IPG, IVLDG )
C SK2N(3,14,3)  - SK2N ( IS2N, ISP, IVLDG )
C SK4C(3,14,3)  - SK4C ( IS2N, ISP, IVLDG )
C
C Common block dictionary:
C
C Name  Type       Description
C ------ ---- ---------------------------------------------
C /SPEED1/:
C
C SK1    R  scf coefficients for HC, CO & NOx for LDGV, LDGT1/2 & MC
C           SH/C/N - the 3 arrays in this BD appear as SK1 in BIGIN1
C           SK1 is partitioned in BD 01 so that the local arrays can be
C           EQUIVALENCEd to its storage area. FORTRAN does not allow a
C           local array to be EQU'd to beyond the first cell of a COMMON
C           array dimension (SK1(1,10,1),SH2(1,1) is illegal), unless
C           the dimension is rightmost (SK1(1,1,2),SC2(1,1) is legal).
C SH     R  HC scf coefficients for IV=1,2,3,8
C SC     R  CO scf coefficients for IV=1,2,3,8
C SN     R  NOX scf coefficients for IV=1,2,3,8
C SK2C   R  low spd <19.6 scf coeffs for the 1st new eq case (A/X+B)
C SK4C   R  HC & CO Mid speeds scf coef for A/Speed + B equation
C
C Local array subscripts:
C
C SH1(6,9) - SH1( ICOEF5, ISP )
C SH2(6,9) - SH2( ICOEF5, ISP )
```

```
C SC1(6,9) - SC1( ICOEF5, ISP )
C SC2(6,9) - SC2( ICOEF5, ISP )
C SN1(6,9) - SN1( ICOEF5, ISP )
C SN2(6,9) - SN2( ICOEF5, ISP )
C SK2CV(2,14,2)  - SK2CV  ( IS2C, ISP, IPG )
C SK2CT1(2,14,2) - SK2CT1 ( IS2C, ISP, IPG )
C SK2CT2(2,14,2) - SK2CT2 ( IS2C, ISP, IPG )
C SK4CV(2,14,2)  - SK4CV  ( IS2C, ISP, IPG )
C SK4CT1(2,14,2) - SK4CT1 ( IS2C, ISP, IPG )
C SK4CT2(2,14,2) - SK4CT2 ( IS2C, ISP, IPG )
C SK2NV(3,14)  - SK2NV  ( IS2N, ISP )
C SK2NT1(3,14) - SK2NT1 ( IS2N, ISP )
C SK2NT2(3,14) - SK2NT2 ( IS2N, ISP )
C
C Local array dictionary:
C
C Name   Type      Description
C ------ ---- ------------------------------------------
C SH1     R   5th degree poly. coef. for SK1 HC  IG=1 thru 9
C SH2     R   5th degree poly. coef. for SK1 HC  IG=10 thru 18
C SC1     R   5th degree poly. coef. for SK1 CO  IG=1 thru 9
C SC2     R   5th degree poly. coef. for SK1 CO  IG=10 thru 18
C SN1     R   5th degree poly. coef. for SK1 NOx IG=1 thru 9
C SN2     R   5th degree poly. coef. for SK1 NOx IG=10 thru 18
C SK2CV   R   Low Speed A/X+B coef. for LDGV HC & CO
C SK2CT1  R   Low Speed A/X+B coef. for LDGT1 HC & CO
C SK2CT2  R   Low Speed A/X+B coef. for LDGT2 HC & CO
C SK4C    R   Mid Speed (A/X+B) coef. for HC & CO
C SK4CV   R   Mid Speed (A/X+B) coef. for HC & CO LDGV
C SK4CT1  R   Mid Speed (A/X+B) coef. for HC & CO LDGT1
C SK4CT2  R   Mid Speed (A/X+B) coef. for HC & CO LDGT2
C
C Notes:
C
C None.
C
C
      COMMON /SPEED1/ SH(6,18),SC(6,18),SN(6,18),SK2C(2,14,3,3),
     *                SK4C(2,14,3,3)
C
      DIMENSION SH1(6,9),SH2(6,9),SC1(6,9),SC2(6,9),SN1(6,9),SN2(6,9)
      DIMENSION SK2CV(2,14,3),SK2CT1(2,14,3),SK2CT2(2,14,3)
      DIMENSION SK4CV(2,14,3),SK4CT1(2,14,3),SK4CT2(2,14,3)
C
      EQUIVALENCE
```

```
     * (SH(1,1),SH1(1,1)), (SH(1,10),SH2(1,1)),
     * (SC(1,1),SC1(1,1)), (SC(1,10),SC2(1,1)),
     * (SN(1,1),SN1(1,1)), (SN(1,10),SN2(1,1)),
     * (SK2C(1,1,1,1),SK2CV(1,1,1)),
     * (SK2C(1,1,1,2),SK2CT1(1,1,1)),
     * (SK2C(1,1,1,3),SK2CT2(1,1,1)),
     * (SK4C(1,1,1,1),SK4CV(1,1,1)),
     * (SK4C(1,1,1,2),SK4CT1(1,1,1)),
     * (SK4C(1,1,1,3),SK4CT2(1,1,1))
C
C 5th degree polynomial HC scf coefficients
C
      DATA SH1/
     *  2.24612E+00, -2.90973E-01, 1.58890E-02,
     *          -4.72494E-04, 6.94077E-06, -3.92798E-08,
     *  2.31026E+00, -2.89572E-01, 1.52990E-02,
     *          -4.46689E-04, 6.48183E-06, -3.63456E-08,
     *  2.16556E+00, -2.69992E-01, 1.44221E-02,
     *          -4.33638E-04, 6.50735E-06, -3.78100E-08,
     *  2.39726E+00, -2.99985E-01, 1.61351E-02,
     *          -4.87491E-04, 7.29093E-06, -4.19769E-08,
     *  2.40873E+00, -3.08187E-01, 1.68168E-02,
     *          -5.06843E-04, 7.53855E-06, -4.31596E-08,
     *  2.23217E+00, -2.84985E-01, 1.53833E-02,
     *          -4.56738E-04, 6.73486E-06, -3.83798E-08,
     *  2.25223E+00, -2.87778E-01, 1.56820E-02,
     *          -4.73179E-04, 7.07954E-06, -4.08456E-08,
     *  2.02779E+00, -2.73049E-01, 1.53577E-02,
     *          -4.60304E-04, 6.78527E-06, -3.84880E-08,
     *  2.15056E+00, -2.83620E-01, 1.53836E-02,
     *          -4.42136E-04, 6.28732E-06, -3.46311E-08/
      DATA SH2/
     *  2.23021E+00, -2.93648E-01, 1.62356E-02,
     *          -4.84148E-04, 7.11591E-06, -4.02861E-08,
     *  2.12230E+00, -2.91072E-01, 1.69089E-02,
     *          -5.26148E-04, 8.02705E-06, -4.70117E-08,
     *  2.15361E+00, -2.83451E-01, 1.56948E-02,
     *          -4.69759E-04, 6.93832E-06, -3.94707E-08,
     *  2.07346E+00, -2.89353E-01, 1.73042E-02,
     *          -5.54707E-04, 8.64204E-06, -5.13107E-08,
     *  2.34948E+00, -3.04959E-01, 1.68416E-02,
     *          -5.09623E-04, 7.59516E-06, -4.34963E-08,
     *  2.11340E+00, -2.85676E-01, 1.63180E-02,
     *          -5.00793E-04, 7.55067E-06, -4.37187E-08,
     *  2.11940E+00, -2.98632E-01, 1.84473E-02,
```

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     *           -6.16544E-04,  9.92062E-06, -6.04021E-08,
     *  2.68382E+00, -3.44633E-01,  1.95417E-02,
     *           -6.25720E-04,  9.78442E-06, -5.83369E-08,
     *  2.39540E+00, -3.35781E-01,  2.11609E-02,
     *           -7.31550E-04,  1.20715E-05, -7.48567E-08/
C
C 5th degree polynomial CO scf coefficients
C
      DATA SC1/
     *  1.81978E+00, -2.54663E-01,  1.52347E-02,
     *           -4.87397E-04,  7.58207E-06, -4.49514E-08,
     *  2.33989E+00, -2.96978E-01,  1.60071E-02,
     *           -4.77396E-04,  7.06752E-06, -4.03978E-08,
     *  2.44154E+00, -2.91473E-01,  1.42949E-02,
     *           -3.87852E-04,  5.29781E-06, -2.82441E-08,
     *  2.46551E+00, -3.05023E-01,  1.60497E-02,
     *           -4.73969E-04,  6.99075E-06, -3.99758E-08,
     *  2.77804E+00, -3.19130E-01,  1.53183E-02,
     *           -4.22327E-04,  5.84948E-06, -3.14969E-08,
     *  2.78899E+00, -3.27107E-01,  1.62943E-02,
     *           -4.67573E-04,  6.71906E-06, -3.74401E-08,
     *  2.70743E+00, -3.31038E-01,  1.76179E-02,
     *           -5.38583E-04,  8.17402E-06, -4.77803E-08,
     *  1.86919E+00, -2.76679E-01,  1.72335E-02,
     *           -5.58279E-04,  8.71678E-06, -5.16980E-08,
     *  1.82133E+00, -2.72054E-01,  1.70304E-02,
     *           -5.52021E-04,  8.62543E-06, -5.11440E-08/
      DATA SC2/
     *  2.01421E+00, -2.95188E-01,  1.86353E-02,
     *           -6.21606E-04,  9.93657E-06, -5.99779E-08,
     *  2.04533E+00, -3.10618E-01,  2.04852E-02,
     *           -7.08527E-04,  1.16215E-05, -7.15690E-08,
     *  2.31868E+00, -3.41147E-01,  2.09446E-02,
     *           -6.65891E-04,  1.02225E-05, -5.98265E-08,
     *  2.57522E+00, -3.28888E-01,  1.89747E-02,
     *           -6.28263E-04,  1.00924E-05, -6.12727E-08,
     *  2.68454E+00, -3.32817E-01,  1.76277E-02,
     *           -5.24123E-04,  7.72221E-06, -4.37025E-08,
     *  2.15487E+00, -3.29116E-01,  2.10112E-02,
     *           -6.89057E-04,  1.08390E-05, -6.47125E-08,
     *  2.54557E+00, -3.62954E-01,  2.32775E-02,
     *           -8.15039E-04,  1.36231E-05, -8.55909E-08,
     *  2.83929E+00, -3.68756E-01,  2.10782E-02,
     *           -6.76438E-04,  1.06267E-05, -6.36405E-08,
     *  2.48747E+00, -3.91562E-01,  2.70721E-02,
```

```
     *           -9.76178E-04,  1.65270E-05,  -1.04317E-07/
C
C 5th degree polynomial NOX scf coefficients
C
      DATA SN1/
     *   2.44424E+00, -2.50107E-01,  1.38293E-02,
     *           -2.87025E-04,  2.07585E-06,  0.00000E+00,
     *   1.68635E+00, -1.18303E-01,  6.54975E-03,
     *           -1.37139E-04,  1.00849E-06,  0.00000E+00,
     *   1.12646E+00, -3.93405E-02,  2.68637E-03,
     *           -6.08024E-05,  4.77286E-07,  0.00000E+00,
     *   1.22677E+00, -4.44978E-02,  2.62476E-03,
     *           -5.67150E-05,  4.34293E-07,  0.00000E+00,
     *   1.01743E+00, -1.18958E-02,  9.14365E-04,
     *           -2.15740E-05,  1.82300E-07,  0.00000E+00,
     *   9.87600E-01, -1.95674E-02,  1.69645E-03,
     *           -4.04000E-05,  3.28001E-07,  0.00000E+00,
     *   1.15917E+00, -4.44536E-02,  2.96425E-03,
     *           -6.68990E-05,  5.22365E-07,  0.00000E+00,
     *   1.88656E+00, -1.61289E-01,  9.04995E-03,
     *           -1.85609E-04,  1.32555E-06,  0.00000E+00,
     *   1.55777E+00, -1.13032E-01,  6.71832E-03,
     *           -1.43409E-04,  1.06079E-06,  0.00000E+00/
      DATA SN2/
     *   2.04516E+00, -1.94014E-01,  1.10736E-02,
     *           -2.31754E-04,  1.68372E-06,  0.00000E+00,
     *   1.63262E+00, -1.21861E-01,  7.03020E-03,
     *           -1.46293E-04,  1.06141E-06,  0.00000E+00,
     *   1.44825E+00, -1.22444E-01,  7.95024E-03,
     *           -1.71078E-04,  1.25777E-06,  0.00000E+00,
     *   2.45969E-01,  8.41954E-02, -3.40841E-03,
     *            6.29880E-05, -4.13975E-07,  0.00000E+00,
     *   1.28169E+00, -8.04874E-02,  5.35735E-03,
     *           -1.18891E-04,  9.01060E-07,  0.00000E+00,
     *   1.53447E+00, -1.25671E-01,  7.85919E-03,
     *           -1.69428E-04,  1.25494E-06,  0.00000E+00,
     *   7.04805E-01,  3.81527E-02, -1.73907E-03,
     *            3.26140E-05, -2.03847E-07,  0.00000E+00,
     *   7.83838E-01,  3.28549E-04,  1.06029E-03,
     *           -3.19350E-05,  2.90389E-07,  0.00000E+00,
     *   9.42131E-01, -4.23240E-02,  3.86253E-03,
     *           -9.39853E-05,  7.53883E-07,  0.00000E+00/
C
C Low Speed ( LT 19.6 ) CF for HC,CO,NOX - SCF equation form A /X + B
C
```

```
C     A     B     A     B     A     B
      DATA SK2CV/
C  HC  IV = 1 LDGV
     H  19.60000, 0.00000,  13.98408, 0.28648,  13.98408, 0.28648,
     H  14.30260, 0.27027,  14.29548, 0.27057,  14.90497, 0.23954,
     H  15.38309, 0.21515,  14.96745, 0.23636,  11.53038, 0.41161,
     H  11.08753, 0.43431,  10.72124, 0.45300,  10.01464, 0.48907,
     H   9.89869, 0.49498,   9.89869, 0.49498,
C  CO
     C  21.28050,-0.08574,  15.17920, 0.22551,  15.17920, 0.22551,
     C  18.64882, 0.04853,  17.80678, 0.09143,  17.54159, 0.10502,
     C  17.70625, 0.09662,  15.58220, 0.20499,  10.15800, 0.48162,
     C   9.23252, 0.52895,   9.51016, 0.51478,   9.45370, 0.51768,
     C   9.48514, 0.51607,   9.48514, 0.51607,
C  NOx (1979=0.0 Not Used)
     N   0.00000, 0.00000,   1.45600, 0.92600,   1.45600, 0.92600,
     N   1.45600, 0.92600,   1.45600, 0.92600,   1.45600, 0.92600,
     N   1.45600, 0.92600,   1.45600, 0.92600,   1.45600, 0.92600,
     N   1.45600, 0.92600,   1.45600, 0.92600,   1.45600, 0.92600,
     N   1.45600, 0.92600,   1.45600, 0.92600/
C
      DATA SK2CT1/
C  HC  IV = 2 LDGT1
     H  19.60000, 0.00000,  14.79943, 0.21458,  14.79943, 0.21458,
     H  15.19938, 0.22452,  12.72329, 0.32482,  13.24083, 0.32444,
     H  13.27086, 0.32291,  13.93844, 0.28885,  11.69134, 0.40351,
     H  11.22095, 0.41764,  10.82497, 0.44772,  10.59274, 0.45852,
     H  10.72619, 0.45276,  10.72619, 0.45276,
C  CO
     C  22.26410,-0.13593,  21.33377,-0.11880,  21.33377,-0.11880,
     C  21.73530,-0.10894,  20.61025,-0.07756,  20.21742,-0.03150,
     C  18.63834, 0.04907,  18.00197, 0.08154,  12.42999, 0.36582,
     C   9.02787, 0.52952,   8.78893, 0.55159,   8.74776, 0.55264,
     C   8.67966, 0.55716,   8.67966, 0.55716,
C  NOx (1979=0.0 Not Used
     N   0.00000, 0.00000,   1.45600, 0.92600,   1.45600, 0.92600,
     N   1.45600, 0.92600,   1.45600, 0.92600,   1.45600, 0.92600,
     N   1.45600, 0.92600,   1.45600, 0.92600,   1.45600, 0.92600,
     N   1.45600, 0.92600,   1.45600, 0.92600,   1.45600, 0.92600,
     N   1.45600, 0.92600,   1.45600, 0.92600/
C
      DATA SK2CT2/
C  HC  IV = 3 LDGT2
     H  19.60000, 0.00000,  14.79943, 0.21458,  14.79943, 0.21458,
     H  15.19938, 0.22452,  12.72329, 0.32482,  13.24083, 0.32444,
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     H 13.27086, 0.32291, 13.93844, 0.28885, 11.69134, 0.40351,
     H 11.22095, 0.41764, 10.82497, 0.44772, 10.59274, 0.45852,
     H 10.72619, 0.45276, 10.72619, 0.45276,
C CO
     C 22.26410,-0.13593, 21.33377,-0.11880, 21.33377,-0.11880,
     C 21.73530,-0.10894, 20.61025,-0.07756, 20.21742,-0.03150,
     C 18.63834, 0.04907, 18.00197, 0.08154, 12.42999, 0.36582,
     C  9.02787, 0.52952,  8.78893, 0.55159,  8.74776, 0.55264,
     C  8.67966, 0.55716,  8.67966, 0.55716,
C NOx (1979=0.0 Not Used)
     N  0.00000, 0.00000,  1.45600, 0.92600,  1.45600, 0.92600,
     N  1.45600, 0.92600,  1.45600, 0.92600,  1.45600, 0.92600,
     N  1.45600, 0.92600,  1.45600, 0.92600,  1.45600, 0.92600,
     N  1.45600, 0.92600,  1.45600, 0.92600,  1.45600, 0.92600,
     N  1.45600, 0.92600,  1.45600, 0.92600/
C
C Mid Speed ( GT 19.6 & LT 48.0 ) for HC,CO,NOx - SCF equation form A/X+B
C
      DATA SK4CV/
C   SK4CV was modified for MOBILE5 Aug 92
C HC IV = 1 LDGV
C    - 1979 -      - 1980 -      - 1981 -
C     A     B      A     B       A     B
     H 19.60, 0.00,  22.66,-0.15,  15.82, 0.19,
     H 14.99, 0.23,  14.44, 0.26,  15.15, 0.23,
     H 14.39, 0.27,  14.69, 0.24,  15.52, 0.21,
     H 16.46, 0.16,  17.42, 0.11,  18.40, 0.06,
     H 18.70, 0.04,  18.70, 0.04,
C CO
     C 19.60, 0.00,  23.13,-0.18,  13.54, 0.31,
     C 13.10, 0.34,   9.08, 0.54,   9.79, 0.50,
     C  9.55, 0.51,  11.47, 0.41,  16.98, 0.13,
     C 20.65,-0.05,  21.12,-0.08,  22.56,-0.15,
     C 23.25,-0.19,  23.25,-0.19,
C NOx
     N  0.00, 0.00,   5.50, 0.71,  -4.20, 1.21,
     N -3.99, 1.20,  -5.25, 1.27,  -4.10, 1.21,
     N -3.84, 1.20,  -3.32, 1.17,  -2.31, 1.12,
     N -1.35, 1.07,  -2.04, 1.10,  -2.49, 1.13,
     N -2.70, 1.14,  -2.70, 1.14/
C
      DATA SK4CT1/
C      - 1979 - was modifed Oct 5, 1992
C HC IV = 2 LDGT1
C     A     B      A     B       A     B
```

```
     H 19.60000, 0.00000, 13.48,  0.31,  13.48,  0.31,
     H 13.49  , 0.31  , 13.45,  0.31,  13.39,  0.32,
     H 13.95  , 0.29  , 14.32,  0.27,  15.44,  0.21,
     H 15.94  , 0.19  , 16.67,  0.15,  17.07,  0.13,
     H 16.95  , 0.13  , 16.95,  0.13,
C CO
     C 19.60000, 0.00000,  9.47,  0.52,   9.47,  0.52,
     C  9.61  , 0.51  ,  9.22,  0.53,   8.77,  0.56,
     C  9.99  , 0.49  , 10.80,  0.45,  16.43,  0.16,
     C 19.84  ,-0.01  , 19.85, -0.01,  21.07, -0.07,
     C 21.71  ,-0.11  , 21.71, -0.11,
C NOx
     N  0.00000, 0.00000, -7.55,  1.39,  -7.55,  1.39,
     N  -7.40 , 1.38  , -7.31,  1.37,  -7.10,  1.36,
     N  -6.31 , 1.32  , -5.14,  1.26,  -2.40,  1.12,
     N  -0.45 , 1.02  , -0.33,  1.02,  -0.46,  1.02,
     N  -0.48 , 1.02  , -0.48,  1.02/
C
C
C
      DATA SK4CT2/
C       - 1979 - was modifed Oct 5, 1992
C HC IV = 3 LDGT2
C      A     B     A     B     A     B
     H 19.60000, 0.00000, 13.48,  0.31,  13.48,  0.31,
     H 13.49  , 0.31  , 13.45,  0.31,  13.39,  0.32,
     H 13.95  , 0.29  , 14.32,  0.27,  15.44,  0.21,
     H 15.94  , 0.19  , 16.67,  0.15,  17.07,  0.13,
     H 16.95  , 0.13  , 16.95,  0.13,
C CO
     C 19.60000, 0.00000,  9.47,  0.52,   9.47,  0.52,
     C  9.61  , 0.51  ,  9.22,  0.53,   8.77,  0.56,
     C  9.99  , 0.49  , 10.80,  0.45,  16.43,  0.16,
     C 19.84  ,-0.01  , 19.85, -0.01,  21.07, -0.07,
     C 21.71  ,-0.11  , 21.71, -0.11,
C NOx
     N  0.00000, 0.00000, -7.55,  1.39,  -7.55,  1.39,
     N  -7.40 , 1.38  , -7.31,  1.37,  -7.10,  1.36,
     N  -6.31 , 1.32  , -5.14,  1.26,  -2.40,  1.12,
     N  -0.45 , 1.02  , -0.33,  1.02,  -0.46,  1.02,
     N  -0.48 , 1.02  , -0.48,  1.02/
C
      END
```