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16. Abstract

The present research project will investigate the fairness of the structure of taxes and charges imposed on Texas highway users. The focus will be on equity between vehicle classes. For each defined vehicle class, the project will estimate the share of total revenues from highway user taxes and charges that the class contributes. For comparison, it will also estimate the share of highway system costs that stem from each class. If the structure of taxes and charges is fully equitable, each class's revenue share will equal its cost share.

This report describes the first phase of our study, which entailed the development of models and databases. The second phase will include scenario-testing based on the results of the first phase; we will examine how potential changes to taxes on Texas road users would affect the tax burden on different vehicle classes. Also planned for the second phase are certain refinements to our models and databases.

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TEXAS HIGHWAY COST ALLOCATION STUDY

by

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Research Report 1810-2

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Highway Cost Allocation in Texas

Conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

in cooperation with the

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

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DISCLAIMERS

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Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

ACP.........................Asphalt concrete pavement
ADT ....Average daily traffic
AMT........................Axle-miles of travel
CTR.........................Center for Transportation Research
ESAL.......................Equivalent single-axle load
FHWA.....................Federal Highway Administration
GM ....Generalized Method
HCA ....Highway Cost Allocation
HDM ....Highway Design and Management (Model)
HRFM ....Highway Revenue Forecasting Model
HPMS......................Highway Performance Monitoring System
MIA.........................Modified Incremental Approach
MTT ....Multi-trailer truck combination
PCE-VMT ....Passenger-car-equivalent vehicle-miles of travel
STT ....Single-trailer truck combination
SU ....Single-unit (truck)
TEA-21 ....Transportation Equity Act for the 21st Century
TRB.........................Transportation Research Board
TxDOT....................Texas Department of Transportation
VIUS ....Vehicle Inventory and Use Survey
VMT........................Vehicle-miles of travel
VTR.........................Vehicle Titles and Registration Division
WIM........................Weigh-in-motion

INTRODUCTION

Highway users pay substantial revenues to governments through fuel taxes, vehicle registration fees, and other taxes and charges. Since the distinction between taxes and other charges is largely immaterial in this report's context, we use "taxes" to refer to all such collections except road and bridge tolls, which do not factor into our modeling.

A highway cost allocation (HCA) study evaluates the fairness of the amounts of tax revenue collected from different classes of highway users. The key results are ratios that compare a class's contribution to tax revenue with its responsibility for highway system costs. One notion of fairness is that each class should pay a share of revenue that equals its share of costs, a yardstick that various highway cost allocation studies have adopted.

The primary criterion with which HCA studies define classes of highway users is the type of vehicle driven. Distinction is made, at a minimum, among passenger cars, buses, single-unit trucks, and combination trucks.

Although a 1997 HCA study by the Federal Highway Administration (FHWA) took a national perspective, many other HCA studies have focused on a particular state. The last in a series of studies for Texas (Euritt et al. 1994) concluded that combination trucks were underpaying relative to other vehicle classes. According to the study's estimates, combination trucks were paying 18.2 percent of the highway-user taxes, but were responsible for 39.2 percent of highway system costs. The "equity ratio"—the ratio of the revenue share to the cost share—was thus 46.4 percent. For buses, the equity ratio was even lower, at 39.7 percent, leading the researchers to conclude that buses, too, were paying less than their share of highway system costs.

The present study goes beyond updating the previous Texas HCA study since it also refines the methods of allocation, particularly for highway system costs. Guiding our choice of allocation methods and the construction of our database was a review of previous HCA studies, especially the last Texas study and the 1997 FHWA study. Parts of the FHWA study were completed after the release of the main report; these parts include a review of state HCA studies that was completed in May 1998. More recently, the FHWA released a software package for conducting HCA studies at the state level (see Stowers et al. 2000). For both cost and revenue allocation, the present study has made use of this software. Published documentation of various models and studies proved sometimes inadequate for our review, and we obtained much of the missing information by contacting the researchers and by examining the spreadsheets from the last Texas HCA study.

1. HIGHWAY COST ALLOCATION STUDIES: ISSUES

1.1 GENERAL ISSUES

COVERAGE OF LEVELS OF GOVERNMENTS

HCA studies vary in their coverage of the levels of government that spend money on roads and collect road-related taxes. The national HCA study conducted by the FHWA (1997) included all levels of government—federal, state and local. The federal government receives revenues from the road users in each state through a range of taxes, principally from those on motor fuel. These revenues flow into the Highway Trust Fund, from which states receive apportionments and allocations for highway spending.

Among state HCA studies as well, some have been comprehensive in their coverage of levels of government. But many have analyzed only the programs of the agency that funded the study: the expenditures for such programs and the highway-user tax revenues that fund the programs. For a review of the state HCA literature, see FHWA (1998b).

The previous Texas HCA studies focused on the road network maintained by the agency funding these studies, the Texas Department of Transportation (TxDOT). Excluded from consideration were expenditures on local government roads, which amounted to about two-fifths of all expenditures on Texas public roads in 1998, the base year for our analysis.[1] Also excluded were the minor tax revenues that local governments collect from road users, mainly registration fees. In 1998, these local government revenues accounted for only about 2 percent of all government tax revenues from Texas road users (see Figure 1.1). The balance derived from state taxes—mainly registration fees and fuel taxes—and from the federal Highway Trust Fund taxes.

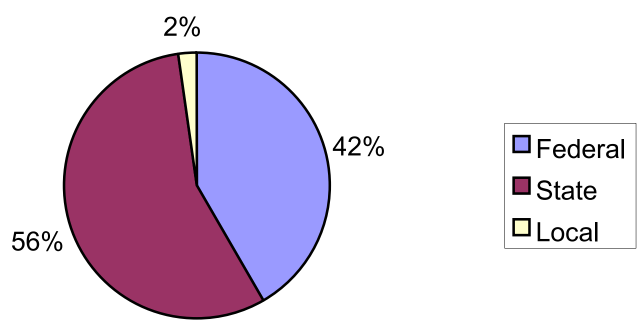

Figure 1.1. Government revenues from Texas motorists, 1998
Source: *Highway Statistics*, tables FE-9, MF-1, MV-2, and LDF

Note: This figure includes revenues from some minor sources not modeled in this study, such as drivers license fees; see Luskin et al. (2001). But it does not include revenues from sales tax on motor vehicles and from road and bridge tolls.

[1] State-maintained roads accounted for virtually all the remainder; expenditures on federally owned roads were minuscule. The local government percentage for expenditures was derived from Table HF-2 of *Highway Statistics 1998* (FHWA 1999).

To keep its scope manageable, the present study follows past precedent in excluding local government from consideration: neither expenditures on local roads nor taxes collected by local government are considered.

DEFINITION OF HIGHWAY USER GROUPS

HCA studies distinguish at least four broad categories of vehicles: automobiles (possibly including motorcycles), buses, single-unit trucks, and combination trucks. Most studies disaggregate these categories into more detailed classes. The 1997 federal HCA study split the truck categories into eighteen classes in Table 1.1, according to type of power unit (straight truck versus truck-tractor), the number of axles, the number of trailers, and the number of tires. The federal study also estimated the cost and revenue shares for different vehicle classes by weight interval.

Most state HCA studies have used broader truck categories than those in the 1997 federal study. The breakdown selected depends partly on the policy questions that a study is meant to elucidate. A few of the state studies have attempted to shed light on the formulation of weight-related fees; these studies estimate equity ratios by type of vehicle and registered weight. A very few state studies have included breakdowns by annual mileage or by industry categories.

Table 1.1. Truck classes used in the 1997 federal HCA study

Single-Unit Trucks	
Light trucks (2 axles and 4 tires)	
Trucks with 2 axles and 6 tires	
Trucks with 3 axles	
Trucks with 4 or more axles	
Combination Trucks with a Single Trailer	
Straight truck-trailer combinations; 3 classes according to the number of axles: ≤ 4, 5, >5	
Truck tractor-semitrailer combinations with 5 axles:	
	2 classes according to whether the rear 2 axles are tandem or split
Other truck tractor-semitrailer combinations; 4 classes according to number of axles:	
	≤ 3, 4, 5, >5
Combination Trucks with Multiple Trailers	
Truck tractors combined with semitrailer and a single trailer;	
	4 classes according to the number of axles: ≤ 5, 6, 7, >7
Triple trailer combinations	

Another important influence on the definition of user groups is data availability. An important source of data for HCA studies has been the Truck Inventory and Use Survey. Now known as the Vehicle Inventory and Use Survey (VIUS) in anticipation of its eventual extension to vehicles other than trucks, the U.S. Census Bureau conducts the survey every five years. HCA studies have drawn on the survey results to estimate, by category of truck, the annual mileage per vehicle, fuel economy, and number of trucks. However, the limited size of the survey's sample can render some of the estimates statistically unreliable at the state level.

Because of this and other data limitations at the state level, the present study uses twelve vehicle classes (Table 1.2 and Figure 1.2) rather than the twenty featured in the federal study. These are the vehicle classes used in one of our major data sources, the Highway Performance Monitoring System (HPMS). Although we have retained the more general term "multi-trailer," which is used in the HPMS classification, Texas does not allow "triple" combinations. The more descriptive term would be "twin trailer," which is what our revenue analysis assumes "multi-trailer trucks" to be. More important to bear in mind, however, is the treatment of vans and sport-utility type vehicles: the HPMS and other FHWA data collections classify them as trucks.

A problem in defining the truck classes is that the number of trailers a truck is pulling can vary over time. A truck may operate as a single unit pulling no trailers, in combination with one trailer, or pulling multiple trailers. The VIUS classifies each truck according to its usual pattern of operation as reported by the survey respondent. On the other hand, the HPMS, which supplies most of our data on vehicle-miles of travel (VMT), is based on traffic counts. It classifies trucks according to their mode of operation when passing the counting site. Since we found no way to resolve these differences between data sources, an element of ambiguity remains in the boundaries between our truck classes.

Table 1.2. Vehicle classes used in the present analysis

Auto	Automobiles (also termed "passenger cars")
Pickup	Single-unit trucks with 2 axles and 4 tires
Other 2 Ax SU	Single-unit trucks with 2 axles and 6 tires
3 Ax SU	Single-unit trucks with 3 axles
4 Ax+ SU	Single-unit trucks with 4 or more axles
4 Ax– STT	Combination trucks with single trailer and 4 or fewer axles
5 Ax STT	Combination trucks with single trailer and 5 axles
6 Ax+ STT	Combination trucks with single trailer and 6 or more axles
5 Ax– MTT	Combination trucks with multiple trailers and 5 or fewer axles
6 Ax MTT	Combination trucks with multiple trailers and 6 axles
7 Ax+ MTT	Combination trucks with multiple trailers and 7 or more axles
Bus	Bus

The data sources are consistent, however, in classifying trucks without regard to recreational or other light trailers. A pickup truck, for example, would not fall into a combination truck category even were it hitched to one of these “utility trailers.” To qualify as a combination, a truck must be pulling a semi-trailer or full-size trailer.

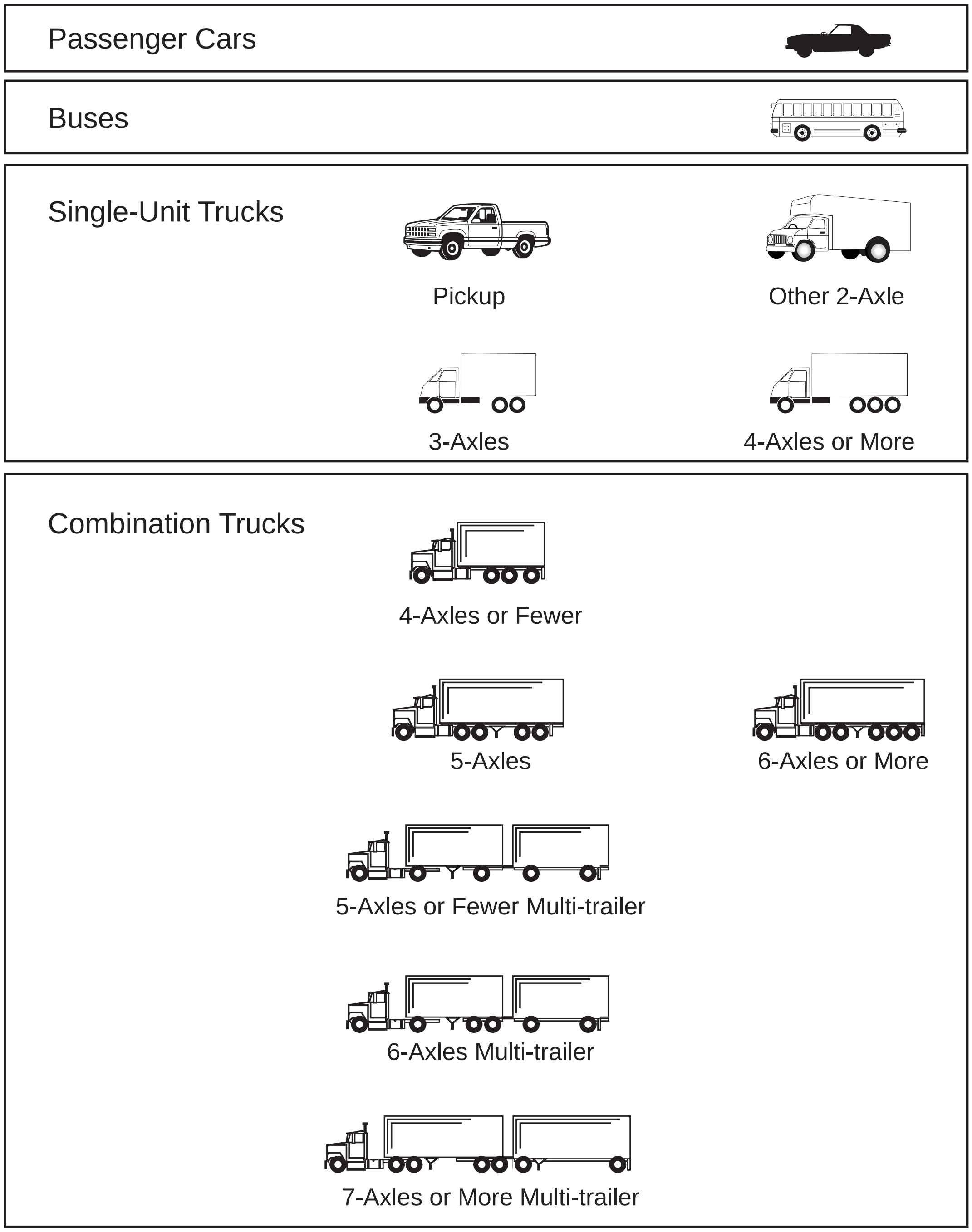

Figure 1.2. Vehicle types

ANALYSIS YEAR

Some HCA studies perform an analysis for each of several years, often with forecasts for future years. For example, the 1994 Texas HCA derived equity ratios for each year from 1992 through 1995. The ratios varied only minimally, however, over this near-term horizon, which argued against performing a similar forecasting exercise in the present study. Forecasting for a longer-term horizon might yield more significant variation in the equity ratios, but would also be highly speculative.

Thus, this study confines its analysis to 1998, the most recent year for which the key data were available when the study commenced. We have not attempted to adjust for differences between fiscal and calendar years. The data on traffic volumes and vehicle numbers are for CY1998, whereas the data on tax revenues and highway expenditures are for FY1998.

Since 1998, there have been minimal changes to the rates or coverage of taxes on Texas highway users. The federal tax rate on gasohol increased by 0.1 cent per gallon on January 1, 2001, and further increases of the same amount are set for the start of 2003 and 2005. The only other change since 1998 was the introduction of a state tax concession on the diesel fuel consumed by certain intercity bus services. Starting FY 1999, the state tax on such fuel effectively declined from 20 cents to 5 cents per gallon. To make our analysis more current, we have conducted it as though the tax rates in effect in 2001 had been in effect in 1998, though we take as given all other conditions in 1998.

1.2 ISSUES IN REVENUE ALLOCATION

The tax revenues paid by a state's highway users are reported in the FHWA's *Highway Statistics* and other sources. *Highway Statistics* reports annual revenues by state, category of tax, and level of government imposing the tax. But such information is merely a starting point for an HCA study, which must estimate the distribution of tax revenues among the defined classes of highway users. This is the "revenue allocation" component of an HCA study

REVENUES USED FOR NON-HIGHWAY PURPOSES

Although revenues from road user taxes are mostly dedicated to highway spending, some are dedicated to other uses. A portion of the revenue from federal road user taxes is earmarked for mass transit, and, between FY1991 and FY1997, another portion was earmarked for deficit reduction. In addition, some of the small amount of revenue from the federal tax on gasohol goes into the federal government's general revenue fund. Similar diversions of road user revenues occur at the state level. In Texas, 25 percent of the net revenues from state fuel taxes (net of administrative expenses) are earmarked for public schools.[2]

Before statistically allocating revenues from road user taxes, some HCA studies, including the previous Texas studies, have excluded amounts of revenue that are not used for highway-related

[2] There is also a very small transfer of state gasoline tax revenue to county highway funds. The amount transferred has been a constant $7.3 M per year since the 1950s, divided among the 254 counties in Texas. Reportedly, some counties do not bother to file for their share.

purposes. But this approach makes the findings of an HCA study sensitive to accounting formalities that have nothing to do with the study's real concerns.

To illustrate this point, suppose that the Texas state government changed its accounting procedures to designate registration fees, rather than fuel taxes, as the source of the money that goes toward education. For this scenario, we assume no changes in government expenditures for education or other purposes. The amounts motorists pay in fuel taxes or registration fees also stay the same; the only change is in the disposition of these revenues in the government accounts. An HCA study that excludes revenues not dedicated for highway purposes would, under this scenario, deduct a portion of registration revenues instead of deducting a portion of fuel tax revenues, as was done in previous HCA studies. Now, the share that each vehicle class contributes differs between fuel taxes and registration fees. Hence, the change in accounting would affect the HCA study's equity ratios, which measure the fairness with which the current system of taxes treats different vehicle classes. But in reality, the change in government accounting would have no effect on how much each vehicle class is paying, which is what really matters in assessing fairness.

Our preferred approach is therefore the same as that in some other HCA studies, which have included all revenues from road user taxes regardless of how the revenues are spent. For comparison, however, we allocate revenue using our preferred approach and, alternatively, counting only the portion of revenues earmarked for highways.

WHICH TAXES SHOULD BE CONSIDERED?

A related problem is the determination of which taxes an HCA study should consider. The previous Texas study considered only the taxes from which a portion of revenues is dedicated to highway use. These are the federal Highway Trust Fund taxes, state vehicle registration fees, and the state taxes on fuel and motor oil.

In contrast, our preferred approach assigns no weight to whether revenues are highway-dedicated, which makes the relevant set of taxes harder to determine.

A general criterion that has guided some HCA studies is that a tax must relate specifically to road use. This would exclude, for example, the revenue from the state sales tax on motor vehicle oils. The previous Texas study included this revenue because it enters the State Highway Fund. However, the revenue is collected under the provisions of a general state sales tax, rather than a tax that relates specifically to road use. The rate of tax that applies to motor vehicle oils is the same as the general rate of sales tax, currently 6.25 percent. Recognizing that our decision is arguable, we have chosen to include the tax revenue from sale of motor vehicle oil. We have not agonized over this decision, since the amount of this revenue is extremely small compared to that from other taxes that this study considers.

On the other hand, we have excluded from our analysis the federal motor fuel tax that funds the Leaking Underground Storage Trust Fund. Since the tax extends to motor fuel used off the highway (railroads, barges, etc,) as well as on, one might view it as more transportation user fee than highway user tax. Because the same was true of the Deficit Reduction Fuel Tax back in 1997, that year's Federal HCA study chose to generally exclude the tax from its analysis. To accommodate some dissenters from this decision, the study also presented alternative results with the tax included. The present study does not perform such an experiment for the Leaking Underground Storage Trust Fund tax because the amount of tax is so small, at 0.1 cent per gallon. What highway users pay for this tax is negligible compared to what they pay in other, specifically highway-related, taxes.

State sales tax on motor vehicles presents a more difficult case. Although the rate of tax is the same as for the general sales tax, there are significant exemptions. The tax does not apply to heavy commercial vehicles that will operate interstate during first year after purchase (as indicated by an "apportioned" registration; see below). Also exempt are vehicles used mainly for farming and ranching. Because of these exemptions and because the tax revenue is so substantial (about $2 billion in FY1998), including the state tax on vehicle sales could appreciably alter the results of our analysis. Our decision to exclude it was based partly on the unavailability of some data, such as the numbers of exempt sales by class of vehicle. The previous Texas HCA study also excluded this tax because the revenues are not dedicated to highway use. (The revenues flow into the general revenue and education accounts.)

REVENUES ENTERING THE HIGHWAY ACCOUNT OF THE FEDERAL HIGHWAY TRUST FUND

The disposition of funds from the highway account of the federal Highway Trust Fund entails some cross-subsidizing among states. Historically, Texas has generally been one of the "net donor" states, which receive from the account less than they contribute through taxes. In 1998, the Transportation Equity Act for the 21st Century (TEA-21) placed limits on the extent to which a state could be a net donor.[3] It guarantees each state a share of apportionments from the highway account equal to at least 90.5 percent of its share of payments.

In practice, the state-level estimates of payments into the highway account are based on data that are two years old. So the minimum guarantee analysis for FY2000 apportionments is based on revenue data for FY1998. In these apportionments, Texas received the minimum guaranteed share, but this must be carefully interpreted. It does not mean that the recovery ratio is 90.5 percent—that Texas will get back exactly that percentage of the revenues that it contributed in 1998. To estimate the recovery ratio, one would have to take account of other factors, including the total amount of apportionments, limitations on obligations of funds, and funds that are "allocated" rather than "apportioned" (see FHWA 1999). Although most of the federal highway funds are apportioned among states under legislated formulas, the distribution of funds for certain programs is through "allocation" in which states have no guaranteed share. Examples are the Interstate Maintenance Discretionary and Bridge Discretionary Programs.

The revenue allocation analysis in some HCA studies treats the amount received from the highway account of the federal Highway Trust Fund, rather than the amount contributed. The last Texas HCA study noted this practice (Euritt et al. 1993, p.9), but chose to allocate the amount contributed, as does the present study. In addition to avoiding the need to estimate a recovery ratio—which would not be straightforward—this approach accords with our preference for counting all revenues paid by Texas road users, regardless of how they are spent.

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[3] More broadly, TEA-21 authorizes the federal surface transportation programs for highways, highway safety, and transit for the 6-year period 1998–2003.

INTERSTATE TRAVEL

Interstate travel complicates HCA analysis from a state perspective. Some vehicles are registered in Texas as "apportioned" under the International Registration Plan in which several Canadian provinces participate along with forty-nine U.S. states and the District of Columbia. The International Registration Plan is a program for licensing commercial vehicles engaged in cross-border operations among member jurisdictions. The owner of an apportioned truck owes to each jurisdiction an amount equal to the normal fee for registering in that jurisdiction multiplied by the share of the vehicle's annual mileage that is traveled there. Vehicles registered as apportioned in Texas include a small number of buses. In our base year, 1998, they also included a substantial number of trailers, which registered as apportioned in order to travel in California. Since then, however, California stopped requiring out-of-state trailers to pay apportioned registration.

The problem that interstate travel posed for our study is that relevant data are lacking. We do not know at the vehicle-class level the proportion of their miles that Texas-registered vehicles drive out of state. Nor do we know the proportion of miles driven within Texas that involve vehicles registered in other states.

A crude allowance for the effect of interstate travel on registration revenues is as follows. First, estimate the revenues from each vehicle class as though interstate travel did not exist: restrict the focus to Texas-registered vehicles and calculate the normal registration fees that apply to them without apportionment. Next, adjust all these estimates of "normal" revenues by the same percentage to produce final estimates that add up to the known total for registration revenues that accrued to Texas. The problem with this two-stage approach is the unrealistic assumption that interstate travel would, for each vehicle class, produce the same percentage difference between "normal" and actual registration revenues.

The last Texas HCA study implemented the two-stage approach separately by broad vehicle class. The classes were those used by TxDOT to supply the FHWA with an estimated breakdown of vehicle registration revenues. (After adjustments, the FHWA reports these estimates in *Highway Statistics.*) The present study has not followed this approach partly because our discussions with TxDOT raised doubts about the accuracy of the estimated breakdown of registration revenues. The other reason for our taking a different tack is that the truck classes now used by TxDOT are much broader than the truck classes used in this study. For trucks, TxDOT distinguishes only "light" from "heavy". Within the heavy category would fall some vehicle classes that engage in substantial interstate travel, such as 5 axle single-trailer combinations, and others that engage in much less, such as single-unit trucks with three axles.[4]

An alternative approach is that incorporated in the state HCA software recently developed for the FHWA (see Stowers et al. 2000.) The software does not require inputs of state data on the number of registered vehicles. Instead, it computes for each vehicle class the number of "vehicle-equivalents," defined as the ratio of annual VMT to average annual mileage per vehicle.

[4] The last Texas HCA study had access to a more detailed breakdown that TxDOT was using at the time to report to the FHWA. TxDOT cross-classified heavy trucks by farm versus nonfarm use and by single-unit versus combination truck. For each of the four resulting categories of heavy trucks, TxDOT estimated the registration revenues paid on the power unit.

Registration revenues are estimated by applying the normal (non-apportioned) fees to each vehicle-equivalent. For illustration, consider the estimates obtained in the present study for five-axle single-trailer combinations. In 1998, these vehicles drove 10,884 million miles within Texas, and per-vehicle annual mileage (driven anywhere) was 70,447 miles (assuming no change from 1997). The total VMT within Texas was thus equivalent to about 154,000 vehicles driven entirely in-state. Registration revenues calculated on this number of vehicle-equivalents should approximate actual registration revenues accruing to Texas, given that apportionment among states is based on mileage.[5]

Turning to federal Highway Trust Fund taxes other than those on fuel, interstate travel poses similar problems for the allocation of revenues. Consider, for example, the federal tax on heavy vehicles (registered weight greater than 55,000 lbs). For a vehicle with a registered weight of, say, 65,000 lbs, the tax will amount to $320 per year. Now imagine the following scenario for two identical trucks of this weight. One truck is registered in Texas and accumulates 30 percent of its mileage out-of-state. Only 70 percent of the tax paid on this truck—$224—represents revenue from Texas road users. The other truck is registered in another state and travels 30 percent of its miles in Texas, and so $96 of its payment of heavy vehicle tax represents revenue from Texas road users. In this somewhat contrived scenario, one would arrive at the correct total tax contribution from Texas road users, the $320 contributed by both trucks in combination, by ignoring trucks registered out-of-state and imagining that Texas-registered trucks drove only within Texas. Ignoring the out-of-state registered vehicles causes understatement of revenues attributable to Texas road use, ignoring the out-of-state mileage of the Texas-registered vehicles causes overstatement, and the errors cancel out.

The last Texas study implicitly assumed this type of canceling out in allocating revenues from federal taxes (other than those on fuel). As with registration revenues, the study allocated these revenues based on the numbers of Texas-registered vehicles, while the new FHWA software allocates revenue based on the number of vehicle-equivalents.

The present study adopts a mixture of these approaches in allocating revenues from registration fees and other taxes on vehicles (including vehicle sales). For truck classes other than light trucks, we base allocation on the number of vehicle-equivalents (the FHWA software approach). For the other vehicle classes—automobiles, light trucks, and buses—we base allocation on the numbers of Texas-registered vehicles (the approach of the last Texas HCA study). These classes engage in much less interstate travel than do heavy trucks, and except for buses, are not subject to apportioned registration. Even among buses, very few are registered in Texas as apportioned — of the 16,463 privately owned buses registered in Texas in 1998, only 354 were registered as apportioned.[6]

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[5] The calculation would be exact, were there no sources of error other than those connected with interstate travel and were annual mileage identical among all vehicles within a class.

[6] TxDOT supplied to CTR a tabulation of apportioned registrations in 1998 by vehicle type. The tabulation showed no passenger cars or light trucks; such vehicles could be registered as apportioned only in special circumstances that are very remote possibilities (see TxDOT 1999b).

1.3 ISSUES IN COST ALLOCATION

Fairness can be defined as the absence of bias and favoritism. Although a highway cost allocation method seeks to identify fair cost responsibilities among the vehicle classes using a common transportation facility, no highway cost allocation procedure is perfect because of the timeless problem of conflicts of interest. Outlined below are some of the issues that make this enterprise a difficult one. Decisions regarding these issues can be considered judgment calls because the issues cannot usually be resolved to universal approval.

Included in this report are results for various alternative methods of cost allocation. We have included them to provide a context within which policymakers and other interested parties may evaluate the merits and demerits of the methods and the assumptions on which they are founded.

EQUITY

Highway cost allocation should be decided equitably. No group should be allocated an unduly large or small share of highway costs. There are, however, different notions of what makes a cost allocation equitable. Groups favored by an allocation that is based on one notion of equity may be disfavored by an allocation that is based on a different notion of equity. Conflicts of interest would arise in such a case because informed groups would not likely be able to separate their desire for equitable cost allocation from their desire to escape great cost responsibility.

In the current study, we have promoted some general principles of equitable cost allocation. While we have employed several possible allocation methods, the methods that we can most confidently endorse are those that maintain the principles of *rationality* and *marginality* as understood in the theory of cooperative games. An earlier report for the current study explained these ideas (Luskin et al 2001). Briefly, rationality is the principle that all groups (here, vehicle classes) should share in the cost savings that are achieved by including all groups in a common facility (here, a statewide highway system for all vehicles). Marginality is the principle that all groups should pay at least the cost incurred by including them in the common facility (their marginal cost of inclusion).

There may be many cost allocations (perhaps greatly disparate ones) that satisfy these principles. Each of these allocations would guarantee that all groups contribute at least their marginal costs and that all groups achieve at least some cost savings. These allocations differ in how they assign additional cost savings beyond those guaranteed by the principle of rationality. The generalized method used in the present study distributes these further cost savings equally among all groups. This method is well established in the cost allocation literature (see Young 1985).

COMMON COSTS

Common costs, also called residual costs, are those that are not clearly the responsibility of any particular group or groups. Two questions arise in the treatment of common costs: how one should account for them and how one should allocate them.

In the current study, common costs are equated with non–load-related costs. Right-of-way acquisition, excavation, pavement striping and marking, grading and drainage, landscaping plus some unclassified costs (including the cost of the base facility) are 100% non-load related costs, and as such they will contribute in their entirety to the total of common costs. Other activities will contribute only partially to this total. In this study, those activities are: preliminary and construction engineering, traffic control and protection, embankment, blading, mobilization and concrete curb and gutter. TxDOT expenditure data were not broken down according to these exact categories. We therefore obtained advice from TxDOT on which of its expenditure categories are purely non-load-related and, for categories that are partially so, the percentage of costs that are non-load-related. Appendix J presents the details of this advice, which came from a panel of TxDOT experts. Other details of our estimation of common costs are presented in Appendix B. We believe that this method of computing common costs was the best method available.

Previous highway cost allocation studies have often allocated common costs proportionally to VMT. The present study also uses this method, which strikes us as a fair one. Other possible allocators include passenger-car-equivalent VMTs (PCE-VMTs) and axle-miles of travel (AMTs).

NUMBER OF LANES

The generalized method, our preferred allocation procedure for several cost components, allocates a cost after considering the costs of hypothetical facilities specially designed for groups or *coalitions* of vehicle classes smaller than the collection of all vehicle classes. We have assumed that the facility designed for any coalition has the same number of lanes.

2. REVENUE ALLOCATION ANALYSIS

To allocate tax revenues, we estimated by class the number of vehicles and VMT. In addition, we broke down these figures along tax-relevant dimensions such as vehicle weight and whether a truck is in farm use. Appendix N presents the detailed breakdowns and explains the estimation procedures.

For each tax, we scaled our estimates of revenue by vehicle class to ensure agreement with a benchmark estimate of total revenue collected from Texas highway users. Except for the state tax on motor oil, the benchmark estimates came from the FHWA publication, *Highway Statistics, 1998.* For the diesel fuel tax, for example, the benchmark was the publication's estimate that $1.538 billion in revenue was attributable to Texas highway users.

For state vehicle registration fees, *Highway Statistics* presents estimates of revenues by category of vehicle and trailer. The trailer categories are commercial and noncommercial. The vehicle categories are passenger cars, motorcycles, buses, farm trucks, and other trucks split between "light" and "heavy." Discussions with TxDOT on the derivation of these estimates convinced us, however, that they are insufficiently precise to serve as benchmarks for our study. The last Texas HCA study used as benchmarks the corresponding TxDOT estimates for earlier years; conceivably, this confidence was warranted at the time.

The following discussion describes the basic provisions of each tax analyzed plus any special provisions that have entered our estimation. The discussion also identifies and assesses the omissions from the analysis and various simplifying assumptions. Sensitivity tests that address uncertainties in the analysis are included in the presentation of results (section 2.3). The most important of these tests involves reallocation of fuel tax revenues to incorporate additional data from the FHWA State HCA software.

2.1 STATE TAXES

Texas exempts from its road-user taxes federal government vehicles and school buses serving public schools.

REGISTRATION FEE

Registration classes

The vast majority of combination trucks are powered by truck-tractors, which have their own "combination" class in the Texas registration system. The fee for a vehicle in this class starts at $148 and increases with combined gross weight to $840 at 80,000 lbs. Truck-tractors that travel interstate travel are registered as "apportioned " and pay a share of the combination fee in proportion to their intrastate mileage."

Semi-trailers are assessed a "token" registration fee, which is normally $15. Full trailers are classified separately and assessed according to their weight. According to staff of the Texas

Department of Public Safety, the full trailer in a multi-trailer combination typically weighs 28,000 lbs. Based on this advice, our analysis assumes the fee for the full trailer to be $225.50. So for a multi-trailer combination registered at 89,000 lbs, our database would record a fee of $1,065.50—the sum of the fees for the truck-tractor, the semi-trailer, and the full trailer.[7]

The other major truck registration class is "commercial," which consists overwhelmingly of single-unit trucks. Within this class, a small number of straight trucks normally operate in combination with a full trailer; these cannot register in the "combination class" since they are not truck-tractors. By treating these vehicles as though they were registered in combination, we simplified our calculations of registration fees with minimal loss of accuracy.

We are only somewhat less comfortable about treating all single-unit trucks as though they were registered as "commercial vehicles." Texas statute defines "commercial vehicles" to include vehicles designed mainly for transporting property, even if they are not actually used for that purpose. As interpreted by TxDOT, this definition gives the owners of sport utility vehicles, some vans, and some minivans the option to register their vehicles as either passenger cars or commercial vehicles with truck plates. Although we lack sound data on the number of such vehicles that are registered as passenger cars, we believe that treating these vehicles as though they were registered as commercial vehicles has introduced only small errors into our analysis.

Private cars have their own registration class with fees that depend on vehicle age and weight. Buses have several registration classes. Buses that do not operate for compensation fall into the "private" bus class. Transit buses, which operate for compensation within a metropolitan area, comprise the "municipal" class. The residual class, "motor" buses, covers all other buses subject to registration fees.

Exemptions and special provisions

Our estimation of registration revenues by vehicle class took account of each of the following special provisions:

- An 11 percent additional registration fee is required of certain diesel-powered vehicles, mainly buses that operate for compensation and heavy single-unit trucks.[8]
- Farm trucks pay a reduced registration fee, equal to only half the normal fee for a "commercial vehicle," and farm trailers pay $5.
- Vehicles owned by governments, including state and local, are exempt from registration fees.

The surcharge for diesel-powered vehicles does not apply to truck-tractors, passenger cars, or private buses. The main classes that attract the surcharge are transit and motor buses and single-unit trucks ("commercial vehicles") with a carrying capacity greater 2,000 lbs. For each class of single-unit truck, our estimate of the percentage of vehicles that are diesel-powered came from the database in the Highway Revenue Forecasting Model, which is described in Appendix N.

[7] To all the registration fees we add 30 cents per vehicle for the reflectorization fee.
[8] Trucks registered in the "combination" or "apportioned" classes are exempt from the additional fee.

Since the database does feature variation in this percentage by registered weight within a vehicle class, our treatment of the diesel surcharge also ignores such variation. Our calculations also ignored the minor consumption of fuels other than diesel fuel by transit and motor buses.[9] Private buses include some that run on gasoline, rather than diesel fuel, but are not subject to the additional registration fee for diesel vehicles.

Appendix N details the estimation for each truck class of the number of farm trucks, and of the numbers of nonfarm trucks by category of owner: private, federal government, and state and local government. As the Appendix explains, "farm truck" can include vehicles hauling timber.

Our estimation of registration revenues by vehicle class ignores various minor provisions in Texas law that affect registration fees—there are simply too many of them to consider. In this category, for example, is the fee exemption for vehicles owned by disabled veterans (more than 23,000 such vehicles in 1998). Other examples include higher fees for the tiny minority of vehicles with solid tires rather than pneumatic tires, the additional $15 assessed on semi-trailers pulled by a truck with an overweight permit, and the aforementioned exemption from the diesel surcharge for trucks with carrying capacity less than 2,000 lbs (they rarely run on diesel fuel).

FUEL TAXES

Tax provisions

Texas levies the following taxes on motor fuels used for road travel: 20 cents per gallon on both diesel fuel and gasoline, and the equivalent of 15 cents per gallon for liquefied gas. For transit buses, however, the tax on diesel fuel is slightly reduced to 19.5 cents per gallon. In addition, for some intercity bus services, the tax on diesel fuel is effectively reduced to a 5 cent per gallon contribution to the state school fund.[10] Intercity bus services qualify for this concession provided that: they

- transport passengers for compensation between points in Texas,
- operate according to a fixed route or schedule, and that the buses
- weigh under 48,000 lbs gross, and
- can transport more than 15 passengers.

In our vehicle classification, transit buses operate within a metropolitan area, while private buses are noncommercial; hence, only motor buses benefit from the concessionary rate of tax of 5 cent per gallon. The Texas Comptroller obtained information from the Texas Bus Association to predict the revenue cost of this concession. According to the Comptroller's analysis, about 39

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[9] In FY1998, about 94 percent of the fuel consumed by transit buses was diesel fuel; see the database of the American Public Transit Association (http://www.apta.com/stats/). Diesel fuel is similarly dominant among intercity buses (see Davis 1999, p. A-24).

[10] In statutory terms, the bus services that qualify for this concession are exempt from the state diesel fuel tax, but must pay a 5 cent per gallon "school fund benefit fee" on their consumption of diesel fuel. See Section 153.203 of the Texas Tax Code and Section 20.002 of the Texas Transportation Code, which is accessible at (http://www.capitol.state.tx.us/statutes/txtoc.html).

million miles of intercity bus travel would have qualified for the concession in 1998, the year before it took effect.

Fuel economy: Trucks

Highway Statistics, 1999 reports estimates of fuel economy in 1998 for broad categories of truck:

- combination trucks
- single-unit trucks with 2 axles
- other single unit trucks

The estimates are at the national-level only and do not distinguish among types of fuel. But for this study's purposes, a more important shortcoming is the lack of additional detail by vehicle class. To remedy these shortcomings, we supplemented the data from Highway Statistics with data from another source.

Initially, the alternative source was the Highway Revenue Forecasting Model. For trucks, the HRFM has enough detail on vehicle classes to yield data for the ten classes of trucks used in the present study. The model also provides 1998 figures for average mileage per gallon by type of fuel, operating weight and detailed vehicle class. These data are actually projections for 1998 that were formed several years earlier, when the model was being developed.

After completion of our draft report, detailed estimates of truck fuel economy became available from the state HCA software developed for the FHWA. Although more current, these estimates are not necessarily superior for our purposes to those from the HRFM. Section 2.4 of this report discusses our use of the FHWA software estimates and presents the results obtained. The rest of the report, however, pertains to the analysis that relied on the HRFM data.

For each combination of truck class, fuel type, and operating weight in the HRFM database, we imported into our database the HRFM estimate of fuel economy (average miles per gallon). The next step was to scaled these figures to agree with those reported for 1998 in *Highway Statistics.* In this way, we combined the advantages of two sources of estimates on truck fuel economy: the greater detail in the HRFM and the inclusion of more recent data in *Highway Statistics*. Among the benefits, this allowed for differences in fuel economy between Texas and the nation that arise from Texas trucks being lighter or heavier than the national average.

Fuel economy: Passenger cars

In calculating fuel economy for passenger cars, the steps and data sources were the same as for trucks. The benefit of using the HRFM was much smaller in the case of passenger cars, however, because our modeling framework includes only once class, "autos", to represent them. So there was no need to disaggregate the *Highway Statistics* estimate for passenger cars into several vehicle classes. The only real benefit of using the HRFM for estimating passenger car fuel economy was to obtain separate estimates by type of fuel. But even this benefit was slight since passenger cars consume little fuel other than gasoline.

Also of slight benefit for estimating fuel economy were the data obtained from TxDOT on passenger car weights. In principle, these data could have allowed us to do for passenger cars what we did for trucks—–to capture the differences in fuel economy between Texas and the nation that arise from Texas vehicles being lighter or heavier than the national average. But the weight intervals in the HRFM are too coarse for this purpose. The intervals are in 5,000 lb increments and nearly all passenger cars weigh less than 5,000 lbs.

Since newer cars tend to be more fuel efficient, an ideal analysis would have allowed for possible differences in car age between Texas and the nation. TxDOT supplied one of the inputs required for this refinement – a distribution of Texas-registered vehicles by vehicle age. But we could not locate data on automotive fuel economy by registered weight and vehicle age, although a cross-tabulation somewhat like this appears in Davis (1999, Table 7-3). Moreover, there are likely to be much more important factors than vehicle age, such as types of roads and congestion levels, that cause automotive fuel economy to differ between Texas and the nation.

Fuel economy: Buses

For transit and motor buses, we estimated the average mileage per gallon for diesel operation. The estimates, 6.2 and 4.1 respectively, came from industry association data for 1998; the sources were the American Public Transit Association (http://www.apta.com/stats/ and, indirectly, the Texas Bus Association (via the Texas Comptroller).

For private buses, we calculated the average registered weight in 1998 based on TxDOT data and then, from HRFM database, the mileage per gallon at that weight for gasoline and diesel fuel separately. Estimated mileage per diesel gallon was much higher for private buses, at 10.8, than for motor or transit buses; this reflects that private buses are lighter and stop less frequently en route.

Composition of fuel consumption

For passenger cars and trucks, we relied on HRFM estimates of the composition of fuel consumption by fuel type. These estimates were available by operating weight interval and, for trucks, by detailed vehicle class.

Apart from private buses, which are not operated for compensation, buses were assumed to consume only diesel fuel. For private buses, lack of data led us to borrow the previous Texas HCA study's assumption that 25 percent of vehicles run on diesel fuel and 75 percent on gasoline.[11] Since we could not ascertain the basis for this assumption, we conducted a sensitivity analysis to examine the effects of alternative assumptions (see Section 2.4).

Estimation of fuel consumption and tax revenues

The next step was to combine the figures on fuel economy and fuel composition with the estimated distribution of VMT in Texas (Appendix N). The results from this step were preliminary estimates of 1998 fuel consumption in Texas by fuel type, vehicle class, and bus subclass. We then scaled these estimates to agree with the Texas totals in *Highway Statistics,*

[11] We asked two large manufacturers of buses about the composition of sales by fuel type, but the information gathered was insufficient for us to replace the previous study's assumption with an alternative in which we had greater confidence.

1998 for fuel consumption by fuel type: gasoline, gasohol and "special fuels" (fuels other than gasoline and gasohol).

After excluding fuel consumed in Texas by federal vehicles (which are exempt from State fuel taxes), we formed our preliminary estimates of State fuel tax revenues by vehicle class. Finally, we scaled these preliminary estimates in uniform proportion to ensure summation to the *Highway Statistics* total for Texas fuel tax revenue.

MOTOR OIL TAX

Sales tax on motor vehicle lubricants generated only 0.4 percent of total revenues from Texas road users in 1998. All government-owned vehicles are exempt.

The HDM-4 model provides parameters for calculating oil consumption by vehicle class given inputs of data on fuel consumption and VMT (Odoki and Kerali n.d.). Table 2.1 gives a mapping from the vehicle classes used in the HDM-4 to the more detailed classes in our study. (Motorcycles are a class in the HDM-4, but not in the present study and so are omitted). To estimate motor oil consumption on Texas highways by vehicle class, we applied this mapping to the HDM-4 parameters and our estimates of fuel consumption and VMT. We then distributed total 1998 revenue from the sales tax on motor oil (as reported to us by the Texas Comptroller of Public Accounts) across vehicle classes in proportion to motor oil consumption.[12]

Table 2.1. Mapping of vehicle classes from HDM-4 Model to Present Texas HCA study

HDM-4 model	Texas HCA study
Passenger car	Passenger car (automobile)
Light truck	Pickup
Light and medium truck	Single-unit trucks excluding pickups
Heavy and articulated truck	Combination trucks
Light and medium bus	Private bus and transit bus
Heavy bus and coach	Motor bus

[12] For comparison, we obtained alternative results based on the previous Texas HCA study estimates of oil consumption per mile traveled by vehicle class. Total oil consumption across all vehicle classes was 21 percent higher in these results than in our HDM-based results. At the vehicle class level, the difference was largest for single-unit trucks, for which the alternative result was about twice as the large as HDM-based result. We have chosen to use the HDM-based results because we know how they were derived, whereas we were unable to ascertain anything about how the previous study obtained its estimates of oil consumption per mile. With the sales tax on motor vehicle lubricants accounting for so little of tax revenues from Texas highway users, the choice between these results was largely inconsequential. As we expected, it made very little difference to our bottom-line findings, the equity ratios in section 4.

2.2 FEDERAL TAXES

The federal taxes considered in this study are those that finance the federal Highway Trust Fund. Vehicles owned by state and local governments, but not the federal government, are exempt from these taxes. School buses are also exempt, even those serving private schools. We discuss the federal taxes in descending order of their revenue contribution. Fuel taxes come first; in 1998, they generated 91 percent of federal tax revenues from Texas road users.

FUEL TAXES

The federal government taxes fuel used for road travel at a per gallon rate of 18.3 cents for gasoline 24.3 cents for diesel fuel. For the relatively small amount of gasohol consumed, the rate is 13 cents. Alternative fuels such as liquefied petroleum gas, although growing in use, contribute so negligible a share to these revenues that most state HCA studies ignore them. In this study, we have included the revenues from alternative fuels used by trucks and passenger cars. For buses, we have assumed all fuel to be diesel fuel or gasoline (as was noted above).

Transit buses are mostly owned by local government authorities and are thus exempt from federal fuel taxes. In addition, some privately owned transit buses—of which there are very few in Texas—are exempt from diesel tax. To qualify for this exemption, the buses must operate a service under contract with, or receive more than a "nominal subsidy" from, a state or local government.[13] We do not know how many of the privately owned transit buses meet this test; we have assumed that none of them do.

Nonexempt buses are taxed on their diesel fuel usage at a preferential rate of 7.3 cents per gallon, provided that they:

- furnish services to the general public for compensation,
- operate scheduled services along regular routes, and
- can seat at least twenty adults.

"Private" buses are ineligible for this concession because they do not operate commercially, while school buses and public owned transit buses are exempt from federal fuel taxes. On the other hand, the small number of private owned transit buses in Texas would tend to qualify and our analysis assumed that all of them do. For motor buses, we perceive the above conditions as being quite similar to those that Texas requires of intercity bus services to qualify for the concession on diesel fuel tax (section 2.1). Our assumption, therefore, is that the federal concession applies to the same amount of motor bus VMT as does the state concession. In 1998, this would have been about 39 million miles (see above section on state fuel taxes.)

Estimation of federal fuel tax revenues by Texas vehicle class proceeded along the same lines as the estimation of state fuel tax revenues. The only difference was that the availability of additional information for federal fuel tax revenues eliminated one step from the procedures. The

[13] See U.S. Internal Revenue Service Publication 510 ("Fuel taxes"), available over the Web at http://www.irs.gov/forms. Privately owned transit buses are few in Texas because transit providers are mainly public and because private providers mainly lease their vehicles from a public owner.

extra information was a breakdown of tax revenues by type of fuel, which *Highway Statistics* does not report for state taxes.

SALES TAX ON HEAVY TRUCKS AND TRAILERS

A sales tax of 12 percent applies to new trucks and trailers with gross vehicle weights greater than 33,000 lbs and 26,000 lbs, respectively. Regulations define gross vehicle weight as the maximum total weight of a loaded vehicle, the same as in the Texas vehicle registration system. Generally, this maximum total weight is the gross vehicle weight rating provided by the manufacturer or determined by the seller of the completed article.

In estimating tax revenue by vehicle class, we assumed that either all components in a vehicle combination exceeded the weight threshold for that tax or that none of them did. In other words, we abstracted from cases where the sales tax applied to the truck but not the trailers, or vice versa. We adopted this simplification because we lacked a cross-tabulation of truck weights by the weights of the attached trailers. FHWA staff have advised us that the loss of realism in this simplification is minor.

Supplementary data for our calculations came from the HRFM and the state HCA software recently developed for the FHWA. For each combination class, we have HRFM estimates of the ratio of annual sales of new vehicles to vehicle stock, as well as estimates from the state HCA software of the prices of new trucks and trailers. The new sales ratio, as with other data we have taken from the HRFM, is a projection for 1998 made some years earlier, and the price data from the state HCA software pertain to 1993. Benchmarking our estimates to the reported Texas revenue total for 1998 overcomes, to a large extent, the datedness of this information.[14]

HEAVY VEHICLE USE TAX

The federal government levies an annual tax on any highway motor vehicle that has a gross weight of 55,000 lbs or more, including the weight of any semitrailers and trailers that the vehicle customarily pulls. The rate of tax is $100 plus $22 for each 1,000 lbs in excess of 55,000 lbs, up to a maximum of $550 (which is reached at 75,000 lbs).

Our estimation of revenue by vehicle class has ignored certain minor provisions of the Heavy Vehicle Use Tax. Vehicles are exempt from the tax if they travel fewer than 5,000 miles per year or, in the case of vehicles used in agriculture, 7,000 miles per year. In addition, a 25 percent

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[14] *Highway Statistics* reports the state contributions to annual revenue from each federal Highway Trust Fund tax. Since there are no data collections on these contributions, the FHWA uses data on motor fuel consumption to estimate a state breakdown of total revenue. The use of fuel consumption data is quite appropriate for fuel taxes: a state that consumes, say, one percent of all gasoline can be reasonably assumed to generate one percent of revenue from federal taxes on gasoline. For the sales tax on heavy trucks and trailers, the FHWA assumes revenue by state to be proportional to state consumption of "special fuels" (fuels other than gasoline or gasohol). The same assumption is made for the other two federal Highway Trust Fund taxes discussed below, which, like the sales tax on heavy trucks and trailers, are borne by heavy vehicles. Despite the obvious element of approximation in this assumption, many HCA studies rely on the *Highway Statistics* estimates of state contributions to federal Highway Trust Fund revenues. In common with the present study, previous Texas studies have used these estimates as benchmarks, scaling their own estimates to conform to the "correct" Texas totals from *Highway Statistics*. Stowers et al (2000) recommend this sort of benchmarking to users of their state HCA software package.

discount from the regular amount of tax applies to vehicles used for logging operations and to vehicles registered in Canada or Mexico.

Estimation of the tax revenue by vehicle class was straightforward, given the simplicity of the tax structure. For buses, we set the tax revenue to zero, as hardly any of them exceed 55,000 lbs. (In the Texas registration files for 1998, there were only about twenty such buses.)

TIRE SALES TAX

The federal sales tax on tires increases with tire weight across several brackets, starting with a tax of zero for anything less than forty lbs. In the top bracket, the tax amounts to $10.50 plus 50 cents per pound in excess of 90 lbs.

Passenger cars fall below the 40-lb threshold for paying the tax. Public transit and school buses are exempt from the tire tax. Commercial buses are exempt under the same conditions as needed to qualify for the diesel tax concession. The only bus travel that generates tire tax is that undertaken by private buses (vehicles not operated for compensation) and motor bus travel that does not qualify for the diesel tax concession. The amount of such motor bus travel in 1998 was about 39 million miles (see appendix N).

To allocate tire tax revenue across vehicle classes, we borrowed values for tire lives and weights from the previous Texas HCA study, which did not document how these values were derived. In response to our request for an opinion, however, the International Tire and Rubber Association wrote that none of the previous study's values "jumped out" as unrealistic. Combined with our estimates of average annual mileage per vehicle, the values from the previous study enabled computation of the annual amount of tire tax sales tax per vehicle. For each combination of truck class and registered weight interval, we multiplied the result of this computation by our estimates of the corresponding number of Texas trucks.

2.3 RESULTS

The inclusion or exclusion of revenues not dedicated to highway spending turns out to have little effect on our results. Tables 2.1–2.3 show the results when such revenues are included, which is our preferred approach. They are quite similar to the results in tables 2.4–2.6, which exclude the federal revenues dedicated to mass transit or the general revenue fund, and the state fuel tax revenues dedicated to education. In highlighting the results of the revenue allocation, we therefore draw only on our preferred results (Tables 2.1-2.3).

For combination trucks, the share of revenue is greater for federal taxes than for state taxes. The predominant combination class—five-axle combinations with a single trailer—generated an estimated 22.2 percent of the federal revenues versus 13.5 percent of state revenues in 1998, our base year. For the light vehicle classes—passenger cars and light trucks (pickups)—the summed estimates displayed the opposite pattern: these classes account for a larger share of states taxes (76.9 percent) than of federal taxes (67.5 percent). The differences stem partly from the federal taxes that fall only on the weightier vehicle classes—the heavy vehicle use tax and the sales taxes on tires and heavy trucks or trailers. The differences also reflect that the Texas government taxes diesel fuel and gasoline at the same per gallon rate, whereas the federal government applies a higher rate to diesel fuel.

2.4 SENSITIVITY TESTS

The calculations for buses depended on debatable assumptions adopted in the absence of certain data for private buses. In addition to assuming that 75 percent of private buses run on gasoline and 25 percent on diesel fuel (see above), we set average mileage per vehicle at 17,000 per year (see Appendix N).

As a sensitivity test, we reversed the fuel proportions, to become 25 percent of private buses running on gasoline and the rest on diesel fuel. This reduced the bus share of tax revenue from 0.41 percent to 0.28 percent. The reduction occurred because diesel engines consume less fuel per mile than do gasoline engines; this outweighed the federal tax rate being higher for diesel fuel than for gasoline. Conversely, assuming that all private buses run on gasoline slightly increased the bus share of tax revenue.

In another sensitivity test, we assumed that private buses average the same annual mileage as do motorcoaches, which are essentially the same as what TxDOT terms motor buses. R.L. Banks (2000) estimated that in 1999 motorcoaches operating in the U.S. and Canada in 1999 averaged 50,600 miles. Substituting this figure for the 17,000 miles we initially assumed for private buses raised the estimated bus share of tax revenue from 0.41 percent to 0.77 percent. The assumption of 50,600 miles is, however, extreme. Although the diversity of functions served by private buses makes it difficult to generalize, a bus manufacturer contacted for this study agreed with our impression that private buses average far fewer miles per year than do motorcoaches.[15]

[15] In addition to churches, major owners of private buses include hospitals and nursing homes, retirement communities, hotels, and car rental companies. Private day care centers and educational institutions also own some of these buses. (In 1997, private schools accounted for about five percent of elementary and secondary school enrollments in Texas; NCES 1999.) Motor buses, in contrast, mostly operate intercity services.

Table 2.2. Revenues from state highway-related taxes, Texas 1998

	Fuel Tax						
	($ thousand)						
	Gasoline*	**Special Fuels****	**Total**	**Registration Fees**	**Oil Tax**	**Total Revenue**	**%**
Auto	1,390,454	19,309	1,409,763	403,076	11,796	1,824,635	54.03
Pickup	532,987	16,646	549,633	216,363	5,431	771,426	22.84
Other 2 Ax SU	73,640	54,509	128,149	41,164	1,720	171,034	5.06
3 Ax SU	2,674	26,766	29,440	35,414	402	65,256	1.93
4 Ax+ SU	36	1,042	1,078	1,454	12	2,544	0.08
4 Ax– STT	3,456	25,794	29,251	12,579	535	42,365	1.25
5 Ax STT	4,023	331,352	335,374	114,088	4,860	454,322	13.45
6 Ax+ STT	31	7,150	7,180	3,178	106	10,464	0.31
5 Ax– MTT	23	11,736	11,758	3,956	184	15,899	0.47
6 Ax MTT	0	2,044	2,044	633	31	2,707	0.08
7 Ax+ MTT	0	306	306	119	4	430	0.01
Bus	5,698	8,111	13,809	1,974	97	15,879	0.47
All Vehicles	2,013,022	504,763	2,517,785	833,998	25,178	3,376,961	100.00

* “Gasoline” includes gasoline and gasohol.

** “Special fuels” includes diesel and other fuels.

Table 2.3. Revenues from federal highway trust fund taxes, Texas 1998

	Fuel Tax							
	($ thousand)							
	Gasoline*	**Special Fuels****	**Total**	**Truck & Trailer Tax**	**Use Tax**	**Tire Tax**	**Total Revenue**	**%**
Auto	1,292,887	21,542	1,314,429	0	0	0	1,314,429	48.63%
Pickup	490,470	18,164	508,634	0	0	423	509,057	18.83%
Other 2 Ax SU	67,942	62,512	130,454	143	0	400	130,997	4.85%
3 Ax SU	2,467	30,719	33,186	10,250	2,408	1,353	47,197	1.75%
4 Ax+ SU	33	1,196	1,229	715	764	43	2,751	0.10%
4 Ax– STT	3,307	29,606	32,913	16,075	511	1,427	50,926	1.88%
5 Ax STT	3,849	380,308	384,156	127,893	61,089	26,225	599,363	22.17%
6 Ax+ STT	30	8,206	8,236	3,570	1,853	543	14,201	0.53%
5 Ax– MTT	22	13,470	13,492	4,539	2,306	970	21,306	0.79%
6 Ax MTT	0	2,346	2,346	699	375	153	3,573	0.13%
7 Ax+ MTT	0	351	352	141	59	25	576	0.02%
Bus	5,662	2,614	8,275	0	0	535	8,811	0.33%
All Vehicles	1,866,667	571,033	2,437,700	164,024	69,365	32,097	2,703,186	100.00%

* "Gasoline" includes gasoline and gasohol.
** "Special fuels" includes diesel and other fuels.

Table 2.4. Revenues from state highway-related and federal highway trust fund taxes, Texas 1998

	State Revenues	Federal Revenues	Total Revenues	%
	($ thousand)			
Auto	1,824,635	1,314,429	3,139,064	51.63
Pickup	771,426	509,057	1,280,483	21.06
Other 2 Ax SU	171,034	130,997	302,030	4.97
3 Ax SU	65,256	47,197	112,453	1.85
4 Ax+ SU	2,544	2,751	5,294	0.09
4 Ax– STT	42,365	50,926	93,291	1.53
5 Ax STT	454,322	599,363	1,053,685	17.33
6 Ax+ STT	10,464	14,201	24,665	0.41
5 Ax– MTT	15,899	21,306	37,205	0.61
6 Ax MTT	2,707	3,573	6,280	0.10
7 Ax+ MTT	430	576	1,005	0.02
Bus	15,879	8,811	24,690	0.41
All Vehicles	3,376,961	2,703,186	6,080,147	100.00

Table 2.5. Revenues from state highway-related taxes, Texas 1998, excluding fuel tax revenues dedicated to public schools

	Fuel Tax						
	($ thousand)						
	Gasoline*	**Special Fuels****	**Total**	**Registration Fees**	**Oil Tax**	**Total Revenue**	**%**
Auto	1,042,841	14,481	1,057,322	403,076	11,796	1,472,194	53.58
Pickup	399,740	12,484	412,224	216,363	5,431	634,018	23.08
Other 2 Ax SU	55,230	40,882	96,112	41,164	1,720	138,996	5.06
3 Ax SU	2,005	20,074	22,080	35,414	402	57,896	2.11
4 Ax+ SU	27	782	808	1,454	12	2,274	0.08
4 Ax– STT	2,592	19,346	21,938	12,579	535	35,052	1.28
5 Ax STT	3,017	248,514	251,531	114,088	4,860	370,478	13.48
6 Ax+ STT	23	5,362	5,385	3,178	106	8,669	0.32
5 Ax– MTT	17	8,802	8,819	3,956	184	12,960	0.47
6 Ax MTT	0	1,533	1,533	633	31	2,197	0.08
7 Ax+ MTT	0	230	230	119	4	353	0.01
Bus	4,274	6,083	10,357	1,974	97	12,427	0.45
All Vehicles	1,509,766	378,572	1,888,339	833,998	25,178	2,747,515	100.00

* "Gasoline" includes gasoline and gasohol.
** "Special fuels" includes diesel and other fuels.

Table 2.6. Revenues from federal highway trust fund taxes, Texas 1998, excluding fuel tax revenues entering mass transit account or the general revenue fund

	Fuel Tax							
	($ thousand)							
	Gasoline*	**Special Fuels****	**Total**	**Truck & Trailer Tax**	**Use Tax**	**Tire Tax**	**Total Revenue**	**%**
Auto	1,084,820	19,082	1,103,902	0	0	0	1,103,902	47.22%
Pickup	411,514	16,090	427,604	0	0	423	428,027	18.31%
Other 2 Ax SU	57,041	55,374	112,415	143	0	400	112,958	4.83%
3 Ax SU	2,071	27,211	29,282	10,250	2,408	1,353	43,294	1.85%
4 Ax+ SU	28	1,059	1,087	715	764	43	2,609	0.11%
4 Ax– STT	2,801	26,226	29,026	16,075	511	1,427	47,039	2.01%
5 Ax STT	3,259	336,882	340,141	127,893	61,089	26,225	555,348	23.76%
6 Ax+ STT	25	7,269	7,294	3,570	1,853	543	13,260	0.57%
5 Ax– MTT	18	11,932	11,950	4,539	2,306	970	19,765	0.85%
6 Ax MTT	0	2,078	2,078	699	375	153	3,305	0.14%
7 Ax+ MTT	0	311	311	141	59	25	536	0.02%
Bus	4,795	2,315	7,110	0	0	535	7,645	0.33%
All Vehicles	1,566,372	505,829	2,072,201	164,024	69,365	32,097	2,337,687	100.00%

* "Gasoline" includes gasoline and gasohol.
** "Special fuels" includes diesel and other fuels.

Table 2.7. Revenues from state highway-related and federal highway trust fund taxes, Texas 1998, excluding revenues not dedicated to highways

	State Revenues	Federal Revenues	Total Revenues	%
	($ thousand)			
Auto	1,472,194	1,103,902	2,576,097	50.66
Pickup	634,018	428,027	1,062,045	20.89
Other 2 Ax SU	138,996	112,958	251,954	4.95
3 Ax SU	57,896	43,294	101,189	1.99
4 Ax+ SU	2,274	2,609	4,883	0.10
4 Ax– STT	35,052	47,039	82,092	1.61
5 Ax STT	370,478	555,348	925,827	18.21
6 Ax+ STT	8,669	13,260	21,929	0.43
5 Ax– MTT	12,960	19,765	32,724	0.64
6 Ax MTT	2,197	3,305	5,501	0.11
7 Ax+ MTT	353	536	889	0.02
Bus	12,427	7,645	20,073	0.39
All Vehicles	2,747,515	2,337,687	5,085,202	100

Alternative treatment of truck fuel economy: FHWA State HCA software

The most important of our sensitivity tests concerns the allocation of fuel tax revenues. As was discussed above, *Highway Statistics* estimates fuel economy for broad categories of trucks. In deriving the results presented thus far, we used data from the HRFM to capture the variation among vehicle classes within these categories. The sensitivity test to be described now replaces these data with default values from the FHWA state HCA software.

The values imported from the FHWA software defined a percent distribution of fuel consumption by fuel type, and averages for fuel economy and per vehicle annual mileage. The values differ between single-unit trucks and combination trucks, and within each of these groups, vary by registered weight (2,000 lb intervals). The averages for fuel economy and per vehicle annual mileage were derived from a complicated analysis of data from the 1997 Vehicle Inventory and Use Survey (VIUS). The complications arose because the size of the survey's sample was inadequate for direct estimation of averages at the level of detail specified in the FHWA database. The averages reported for an individual state were therefore based on a synthesis of data from the various states, rather than on data for that state alone (see Sydec, Inc. 2000).

Whether the substitution of the FHWA default values for the HRFM data improves accuracy is not altogether clear. The default values we have imported are somewhat specific to Texas and are based on more current survey evidence, but the estimates from the HRFM are based on engineering as well as survey evidence. As with our previous calculations, exclusion of revenues not dedicated to highways has virtually no affect on the results; hence, we present the results only for the case where all revenues are counted.

For the most part, the results based on the FHWA default values (tables 2.8-2.10) differ little from those based on data from the HRFM (tables 2.2-2.4). Since the estimates of motor oil consumption depend positively on the estimates of fuel consumption, the differences extend to the results for the motor oil tax. The most significant differences pertain to the 3- and 4-axle single-unit trucks, for which the FHWA default values yields higher estimates of fuel and motor oil tax revenue.

In addition to the values for truck fuel consumption and mileage, our analysis also imported from the FHWA software the values for truck and trailer prices; these were used in allocating revenues from the sales tax on heavy trucks and trailers (section 2.2). Apart from these data, however, our careful review of the FHWA software did not reveal features that we believed would materially improve our revenue allocation analysis. The challenges in revenue allocation analysis are mainly the large demands for data, much of which the FHWA software leaves users to supply. In particular, the users must supply the parameters for vehicle registration fees and the VMT distributions by registered weight and vehicle class. In contrast with cost allocation, there is little in the way of a "theory" of revenue allocation embodied in the FHWA software or other HCA frameworks.

Table 2.8. Revenues from state highway-related taxes, Texas 1998, Fuel tax shares estimated with FHWA state HCA software

	Fuel Tax						
	($ thousand)						
	Gasoline*	**Special Fuels****	**Total**	**Registration Fees**	**Oil Tax**	**Total Revenue**	**%**
Auto	1,422,356	17,745	1,440,100	403,076	11,899	1855076	54.93
Pickup	474,531	58,665	533,196	216,363	5,373	754932	22.36
Other 2 Ax SU	97,312	29,417	126,729	41,164	1,714	169608	5.02
3 Ax SU	9,917	34,212	44,130	35,414	443	79987	2.37
4 Ax+ SU	13	1,505	1,518	1,454	14	2985	0.09
4 Ax– STT	2,897	29,311	32,208	12,579	543	45330	1.34
5 Ax STT	2,283	303,420	305,703	114,088	4,772	424563	12.57
6 Ax+ STT	24	6,711	6,735	3,178	104	10017	0.30
5 Ax– MTT	39	11,870	11,910	3,956	185	16051	0.48
6 Ax MTT	5	2,006	2,011	633	31	2675	0.08
7 Ax+ MTT	1	267	268	119	4	391	0.01
Bus	5,703	7,573	13,277	1,974	96	15346	0.45
All Vehicles	2,015,082	502,703	2,517,785	833,998	25,178	3,376,961	100.00

* "Gasoline" includes gasoline and gasohol.
** "Special fuels" includes diesel and other fuels.

Table 2.9. Revenues from federal highway trust fund taxes, Texas 1998, Fuel tax shares estimated with FHWA state HCA software

	Fuel Tax							
	($ thousand)							
	Gasoline*	**Special Fuels****	**Total**	**Truck & Trailer Tax**	**Use Tax**	**Tire Tax**	**Total Revenue**	**%**
Auto	1,303,336	20,004	1,323,339	0	0	0	1,323,339	48.95%
Pickup	451,605	71,028	522,633	0	0	423	523,056	19.35%
Other 2 Ax SU	91,958	33,750	125,709	143	0	400	126,252	4.67%
3 Ax SU	9,271	39,213	48,484	10,250	2,408	1,353	62,495	2.31%
4 Ax+ SU	12	1,725	1,736	715	764	43	3,258	0.12%
4 Ax– STT	2,672	33,397	36,069	16,075	511	1,427	54,082	2.00%
5 Ax STT	2,101	345,727	347,828	127,893	61,089	26,225	563,035	20.83%
6 Ax+ STT	22	7,647	7,669	3,570	1,853	543	13,634	0.50%
5 Ax– MTT	36	13,525	13,562	4,539	2,306	970	21,376	0.79%
6 Ax MTT	0	2,286	2,286	699	375	153	3,513	0.13%
7 Ax+ MTT	0	304	304	141	59	25	529	0.02%
Bus	5,654	2,427	8,081	0	0	535	8,617	0.32%
All Vehicles	1,866,667	571,033	2,437,700	164,024	69,365	32,097	2,703,186	100.00%

* "Gasoline" includes gasoline and gasohol.
** "Special fuels" includes diesel and other fuels.

Table 2.10. Revenues from state highway-related and federal highway trust fund taxes, Texas 1998, Fuel tax shares estimated with FHWA state HCA software

	State Revenues	Federal Revenues	Total Revenues	%
	($ thousand)			
Auto	1,855,076	1,323,339	3,178,415	52.28
Pickup	754,932	523,056	1,277,987	21.02
Other 2 Ax SU	169,608	126,252	295,860	4.87
3 Ax SU	79,987	62,495	142,482	2.34
4 Ax+ SU	2,985	3,258	6,243	0.10
4 Ax– STT	45,330	54,082	99,412	1.64
5 Ax STT	424,563	563,035	987,598	16.24
6 Ax+ STT	10,017	13,634	23,651	0.39
5 Ax– MTT	16,051	21,376	37,427	0.62
6 Ax MTT	2,675	3,513	6,188	0.10
7 Ax+ MTT	391	529	920	0.02
Bus	15,346	8,617	23,963	0.39
All Vehicles	3,376,961	2,703,186	6,080,147	100.00

3. COST ALLOCATION ANALYSIS

3.1 CLIMATIC REGIONS

Climatic factors such as temperature, precipitation, evaporation, and freeze-thaw cycles affect the durability of highways. Differences in climate from one place to another cause to differences in highway rehabilitation and maintenance costs from place to place. A thorough cost analysis of rehabilitation and maintenance must account for these cost differences. We have done this in the current study by dividing the state of Texas into five roughly homogeneous climatic regions and performing our analyses region by region. The climatic decomposition required to establish these climatic regions was performed in a study by Garcia-Diaz (1988). In this study, thirteen climatic factors that differentiate local climates were identified. These climatic factors are:

- Thorntwaite Index (TI)
- Average winter temperature (AVT1)
- Average summer temperature (AVT2)
- Total freeze-thaw cycles in one year (FT)
- Total precipitation or rainfall from Month 4 to Month 8 (R)
- Minimum monthly moisture change (MC1)
- Maximum monthly moisture change (MC2)
- Actual evapotranspiration in one year (AE)
- Days with precipitation in one year (DP)
- Highest monthly mean maximum temperature (MMT)
- Mean potential evapotranspiration (PE)
- Mean maximum days with continuous precipitation (MDCP)
- Total wet freeze-thaw cycles in one year (WFT)

These factors were analyzed for their statistical significance in affecting climate. It was found that the statistically significant factors were TI, AVT1, FT, and R. Based on these results, the researchers performed a cluster analysis that grouped all Texas highway districts into five climatic regions. The districts in each climatic region are given in Table 3.1, and a map showing the layout of the climatic regions is given in Figure 3.1.

3.2 DATA SOURCES

The procedure used in the current study requires cost estimates for various highway construction and maintenance projects. The formulas that give these cost estimates are based on historical data for items such as expenditures and traffic.

The following sources of traffic data from TxDOT were used in the current study to determine highway use by various vehicle classes:

- 1998 Road Inventory File
- 1998 Vehicle Classification Report
- TxDOT axle distribution data file

Table 3.1. Climatic regions and their districts

Region 1 East Texas	**Region 2** West Texas	**Region 3** Texas Panhandle	**Region 4** South Texas	**Region 5** North-Central Texas
Atlanta Beaumont Houston Lufkin Paris Tyler	Abilene El Paso Odessa San Angelo	Amarillo Childress Lubbock	Corpus Christi Laredo Pharr San Antonio Yoakum	Austin Brownwood Bryan Dallas Fort Worth Waco Wichita Falls

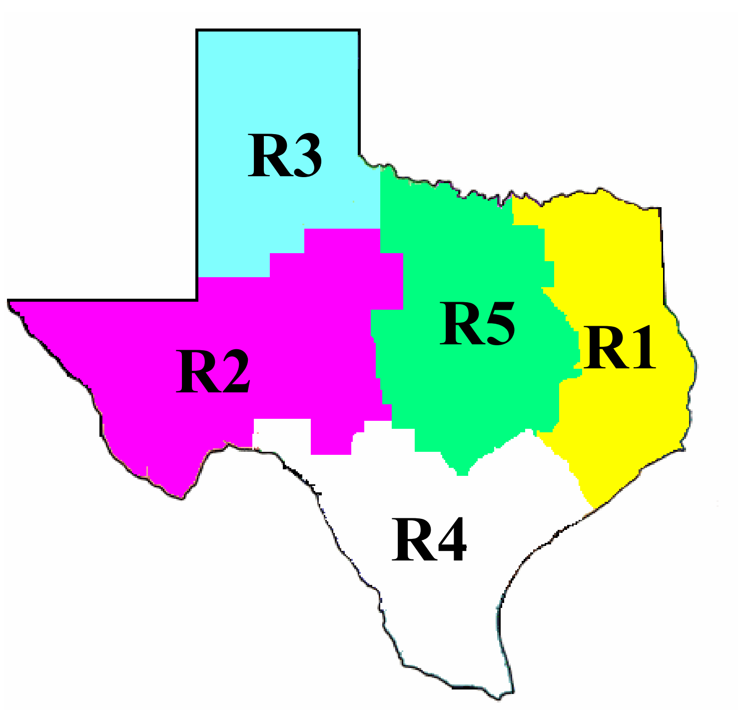


Figure 3.1. Map of climatic regions

Bid data from TxDOT were used to estimate the costs of paving materials: asphalt concrete pavement, concrete pavement, lime-stabilized base, flexible base, and cement-treated base. Historical bridge construction project data (1998 letting) from TxDOT were used to estimate the costs of bridge construction.

TxDOT data on historical costs for pavement construction, pavement maintenance and rehabilitation, and miscellaneous highway administration tasks were also used in the current study.

Some of the above data were used as input in the following cost-estimation computer programs:

- FPS19 to estimate flexible pavement construction costs
- RENU3 to estimate pavement rehabilitation and maintenance costs
- TSLAB and KSLAB to estimate rigid pavement construction costs

3.3 ADT VS. VMT

For some cost components, the measure of traffic volume in the cost allocation analysis was VMT, the same as in the revenue allocation analysis. For other cost components, the measure of traffic volume was ADT from the 1998 Vehicle Classification Report. As Table 3.2 shows, the distribution of traffic volume among vehicle classes differs little between these measures. To facilitate comparison with the ADT data, which are collected only for state-maintained roads, Table 3.2 excludes local road traffic from the VMT calculations. The revenue allocation analysis, however, included VMT on local roads.

Table 3.2. ADT vs. VMT, Texas 1998

	Total ADT	VMT (million)	ADT (percent)	VMT (percent)
Auto	9,560,368	119,472	68.428	66.197
Pick up & panel	2,686,861	39,003	19.231	21.611
Other 2Ax SU	486,895	7,077	3.485	3.921
3 AX SU	122,183	1,544	0.875	0.856
4 Ax+ SU	2,894	50	0.021	0.027
4 Ax- STT	84,302	1,178	0.603	0.653
5 AX STT	928,488	10,828	6.646	6.000
6 Ax+ STT	15,729	238	0.113	0.132
5 Ax- MTT	36,161	418	0.259	0.232
6 Ax MTT	6,279	69	0.045	0.038
7 Ax+ MTT	435	9	0.003	0.005
Bus	40,849	594	0.292	0.329
Total	13,971,444	119,472	100.000	100.000

3.4 COST COMPONENTS

Four major cost components were considered for allocation to the various vehicle classes:

- Pavement construction costs (including reconstruction costs)
- Pavement rehabilitation and maintenance costs
- Bridge costs
- Other costs (common costs)

The "other costs" are the residual costs, which consist of non–load-related costs such as engineering costs and purchase of right-of-way. Bridge rehabilitation and maintenance costs were not considered separately. Instead, they were allocated together with all other bridge costs. In the previous Texas HCA study, bridge rehabilitation and maintenance costs were not allocated apart from total bridge costs because Texas bridge rehabilitation and maintenance expenditures were found to be only about 12 percent of total bridge costs (Hudson et al. 1987).

3.5 FLEXIBLE PAVEMENT CONSTRUCTION COSTS

Pavement construction cost allocations were determined for both flexible pavement and rigid pavement. This section considers the flexible pavement construction cost allocation.

The FPS19 program was used to estimate the construction cost for flexible pavement that is expected to withstand the application of a certain number of equivalent single-axle loads (ESALs). To return a cost estimate, the program required the following information:

- the pavement layers that constitute the pavement structure for a particular road type
- the initial serviceability index desired for the road (which influences the thickness of each layer)
- the cost of each layer in dollars per cubic yard
- the number of ESALs expected to be applied over the course of the road's life

The following subsections describe how this information was collected and analyzed.

PAVEMENT LAYERS AND INITIAL SERVICEABILITY INDEX

Six major road types were arranged into three groups:

1. Interstate highways
   High-traffic U.S. highways
   High-traffic state highways

2. Low-traffic U.S. highways
   Low-traffic state highways

3. Farm-to-market roads

Our assumptions are that within each group, all road types are constructed with the same pavement layers and are built to have the same initial serviceability index. Our analysis recognizes, however, that the groups differ in these characteristics (Table 3.3).

Table 3.3. Flexible pavement layers and initial serviceability index by highway type

Highway Type	Pavement Layers	Initial Serviceability Index
Interstate & high-traffic U.S./state	ACP asphalt-stabilized base flexible base subgrade	4.5
Low-traffic U.S./state	ACP flexible base lime-stabilized base subgrade	4.2
Farm-to-market	ACP flexible base subgrade	4.0

The intended terminal serviceability index for each road type group is 3.0.

PAVEMENT MATERIAL COSTS

Table 3.4 gives the costs by region of each pavement material in dollars per cubic yard.

The figures are drawn from TxDOT bid data.

Table 3.4. Flexible pavement material costs by region

Region	ACP ($/C.Y.)	Flexible Base ($/C.Y.)	Lime-stabilized Base ($/C.Y)	Surface Treatment ($/S.Y.)
1	$78.96	$27.51	$14.86	$2.19
2	$69.10	$15.75	$10.16	$1.88
3	$79.49	$10.71	$10.33	$2.02
4	$66.17	$16.40	$ 8.36	$1.81
5	$68.37	$24.36	$12.67	$2.00
Texas Average	**$71.39**	**$20.81**	**$11.57**	**$1.98**

These costs are for the following pavement material item numbers:

- Asphalt concrete pavement 3146
- Flexible base 247
- Lime-stabilized base 260

The estimated statewide cost for asphalt-stabilized base is $66.82 per cubic yard.

ESALS

Average daily traffic (ADT) figures were calculated from the vehicle classification report. By using average ESALs per vehicle pass by vehicle type, these were used in turn to calculate the expected number of ESALs to be applied to the roads. The details for the calculation of average ESALs per vehicle pass by vehicle type is given in Appendix L.

MODEL FOR PAVEMENT CONSTRUCTION COSTS

Any road, even with low traffic volume, requires a *base facility*: a pavement with a minimum thickness and a minimum number of lanes. The base facility is a hypothetical pavement that would provide minimal traffic capacity as well as durability for environmental impact and minimal traffic loadings. Software such as FPS (Flexible Pavement Design System) (1997) and KSLAB can be used to determine the minimal traffic loadings.

Similarly, any road requires a minimum number of lanes, or *base lanes*. As the traffic volume on a road increases, more lanes may be required —these are termed *additional lanes*. In our study, however, the number of lanes is assumed to be fixed in all allocation methods except the variable number of lanes scenario.

The following pavement structure (Figure 3.2) is considered as the base facility structure for all roads. The number of lanes would depend on the traffic mix and traffic volume.

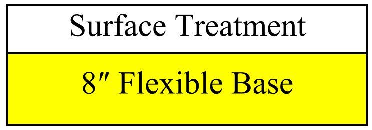


Figure. 3.2. Minimum pavement structure

For each combination of region and road type, the FPS19 software calculated flexible pavement construction cost estimates for several levels of expected applied ESALs. We found that for interstate and U.S./state highways a good model for the relationship between the cost of pavement and the number of ESALs is the one shown below:

$$Y = l(a + b\sqrt{X\ F(l)}) \tag{3.1}$$

where Y is the cost in dollars per square yard, l is the number of lanes, X is the number of ESALs, $F(l)$ is a lane distribution factor, parameter a is an estimate of the cost of a minimum-thickness pavement, and parameter b is a value that depends on the geographic region and the road type. A lane distribution factor specifies the percentage of the total one-way 18-kip ESALs for the design lane. The value of l is assumed to be fixed in all allocation methods except the variable-number-of-lanes scenario. Furthermore, the cost function shown in equation (3.1) is a concave function with good mathematical properties.

For farm-to-market roads, equation (3.2) was found to have a better goodness of fit than equation (3.1):

$$Y = l(a + b\sqrt{(X - m)\ F(l)}) \tag{3.2}$$

In this relationship, m is the number of ESALs corresponding to minimum pavement thickness. All other symbols are as defined for equation (3.1). In equation (3.2) if X is less than m, then Y is assumed to be equal to la.

Table 3.5 gives lane distribution factors used in Texas.

Table 3.5. Lane distribution factors used in Texas

Number of lanes in each direction	Lane distribution factors
1 or 2	1.0
3	0.7
4 or more than 4	0.6

The parameter *a*, which defines minimum pavement construction costs for no traffic loads, was assigned the same value in equations 3.1 and 3.2. It was calculated assuming a minimum pavement structure and using available pavement material prices. For farm-to-market roads, the parameter *m* (number of ESALs corresponding to the minimum pavement structure) is determined by using the FPS software. Table 3.6 shows calculated values for both these parameters.

Table 3.6. Flexible pavement construction cost function: Estimates of parameters *a* and *m*.

Region	*a*	*m*
1	58,432.0	200,000
2	37,875.2	600,000
3	46,604.8	200,000
4	38,368.0	400,000
5	52,166.4	400,000

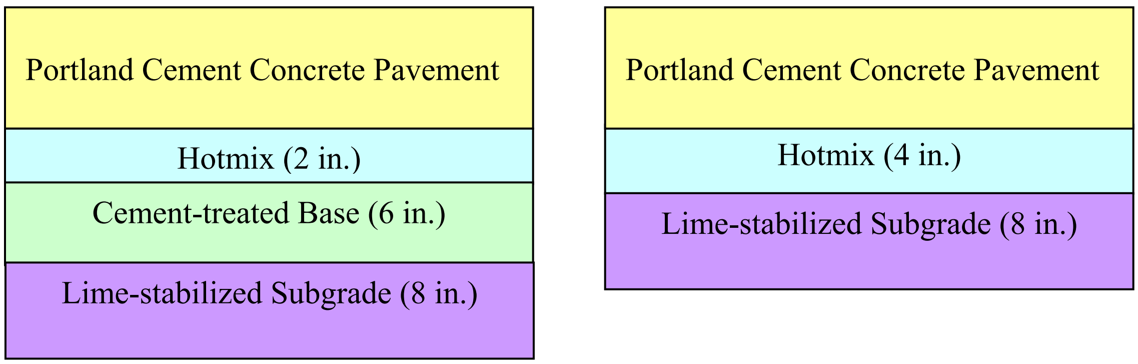
The values of parameter *b* were estimated by statistically regressing the cost per lane-mile (the dependent variable) on the number of ESALs (the independent variable). Separate regression analyses were performed for the different climatic regions. Five data points were used for interstate and farm-to-market roads, and seven points for US/State highways. The selected variation in the number of ESALs varied by regression: from two million to 16 million for interstate highways, from 200,000 to one million for farm-to-market roads, and from 500,000 to four million for US/State highways. Table 3.7 shows estimates of parameter *b*, along with a statistical measure of goodness of fit (R^2 values).

Table 3.7. Flexible pavement construction cost function:
Estimates of parameter *b* and of R^2

Region	IH		US/SH		FM	
	b	R^2	*b*	R^2	*b*	R^2
1	66.86	0.98	69.30	0.94	31.65	0.90
2	58.55	0.99	47.02	0.64	7.50	0.72
3	83.64	0.98	76.65	0.91	25.67	0.88
4	52.57	0.98	45.31	0.68	7.52	0.86
5	59.04	0.98	57.58	0.89	18.49	0.71

3.6 RIGID PAVEMENT CONSTRUCTION

To develop a model relating rigid pavement construction costs to the number of ESALs, we used the TSLAB program to estimate the construction costs of the two rigid pavement types used in Texas. The two pavement types are shown in Figure 3.3.



(a) Houston (b) Other Regions

Figure 3.3. Rigid pavement design

For each of these designs, the only variable dimension is the thickness of the top layer of cement. Table 3.8 gives the costs by each pavement material in dollars per cubic yard. The figures are drawn from TxDOT bid data. Using the constants in Table 3.9, we used TSLAB to calculate the required thickness and expected cost of rigid pavement construction for several numbers of expected ESALs.

After calculating the cost estimates, we obtained an equation that defines cost as a function of the number of ESALs expected to be applied to the road:

$$Y = l\,(a + b\sqrt{X\,F(l)}) \tag{3.3}$$

where *Y* is the cost in dollars per square yard, *l* is the number of lanes, *X* is the number of ESALs, *F*(*l*) is a function for lane distribution factors, *a* is the cost for minimum pavement thickness, and *b* is a parameter that depends on the geographic region and the road type. Regression analysis yielded our estimates of the parameter *b* by region along with the R^2 values. Estimates by region of the parameter *a* (Table 3.10) were calculated from pavement material prices and minimum slab thickness (5 inches).

Table 3.8. Rigid pavement material costs per cubic yard

Material	Cost
Concrete	$105.00
Hotmix	$71.02
Cement-treated base	$34.06
Lime-stabilized subgrade	$11.57

Table 3.9. Input values for TSLAB

Design Factor	Numerical Value
Mean concrete rupture modulus	650 psi
Concrete elastic modulus	4.2 million psi
Effective modulus of subgrade reaction	300 pci
Terminal serviceability index	2.5
Initial serviceability index	4.5
Load transfer coefficient	2.9
Drainage coefficient	1.03 (Houston) 1.00 (Other areas)
Overall standard deviation	0.39
Reliability	85% (<10 million ESALs) 95% (10-30 million ESALs) 99% (>30 million ESALs)

Table 3.10. Rigid pavement construction cost function: Estimate of parameter *a*

Region	*a* ($/lane-mile)
Houston	188,652
Other regions	176,610

Table 3.11. Rigid pavement construction cost function: Estimates of parameter *b* and of R^2

Region	*b*	R^2
Houston	26.22	0.97
Other regions	26.96	0.97

3.7 BRIDGE CONSTRUCTION COSTS

The previous Texas HCA study used federal data to estimate construction costs for bridges that support less weight than do bridges in Texas. The present study borrows these estimates; for bridges that would support more weight than those in Texas, estimates of bridge construction costs were taken from Moses (1989). Table 3.12 expresses the estimates from both sources as percentages of a baseline cost, which is the construction cost per lane-mile for a Class HS20 bridge. To estimate the cost per lane-mile for each of the five climatic regions of Texas, we multiplied these percentages by the region's baseline cost thus defined. Table 3.13 presents the results.

We then estimated equation (3.4), which defines cost per lane-mile as a function of the gross vehicle weight to be supported:

$$Y = l\,(a + b\,X) \tag{3.4}$$

where *Y* is the cost in dollars per lane-mile, *X* is the gross vehicle weight in kips, and *a* and *b* are constants that depend on geographic region. Estimates of the parameters *a* and *b* in equation (3.4) were obtained by regression analysis and appear in Table 3.14.

Lastly, the fitted equation 3.4 was used to allocate bridge construction costs. See Appendix H for an illustration of the allocation method.

Table 3.12. Construction cost of bridges by weight capacity, as a percentage of construction cost of a baseline HS20 bridge

Gross Vehicle Weight (kips)	5	10	20	30	40	54	72	90	108
Class	H2.5	H5	H10	H15	H20	HS15	HS20	HS25	HS30
Cost	80.78	82.61	86.52	90.43	95.80	94.59	100	105	110
	From the previous study (1992-1994)							Moses study (1989)	

Table 3.13. Cost of H20 bridge construction by region in millions of dollars per lane-mile

Region	Cost
1	2.9
2	3.1
3	2.4
4	2.4
5	2.2

Table 3.14. Bridge construction cost function, parameter estimates

Region	*a*	*b*
1	2.4×10^6	7926.2
2	2.5×10^6	8370.9
3	1.9×10^6	6465.3
4	2.0×10^6	6574.3
5	1.8×10^6	5998.4

3.8 FLEXIBLE PAVEMENT REHABILITATION AND MAINTENANCE

The RENU3 program was used to calculate rehabilitation and maintenance cost estimates for flexible pavements. Based on a cost matrix (see Appendix D for details), the program returns a cost estimate for a given serviceability index and a given ADT figure. After converting ADTs to ESALs, we found a good model for estimating costs as a function of ESALs to be:

$$Y = l\ (a + b\ X\ F(l)) \tag{3.5}$$

where Y is the cost in dollars per square yard, X is millions of ESALs per year, $F(l)$ is a function for lane distribution factors, and a and b are parameters that depend on region and road type. Values of the parameters a and b were estimated by regression analysis and are shown in Table 3.15.

Table 3.15. Rehabilitation and maintenance cost function, parameter estimates

Region		Interstate & high-traffic U.S./state	Low-traffic U.S./state	Farm-to-market
1	*a*	0.65	0.28	0.26
	b	1.70	2.52	3.55
2	*a*	0.18	0.00	0.09
	b	6.09	6.75	3.85
3	*a*	0.01	0.08	0.13
	b	1.98	0.81	0.05
4	*a*	0.51	0.23	0.21
	b	1.46	2.14	3.04
5	*a*	0.67	0.32	0.31
	b	1.44	2.16	3.02

3.9 NUMBER OF LANES

The approximate numbers of lanes needed for all sample highway sections were calculated based on the guidelines given in the 1997 TRB Highway Capacity Manual.

Non-interstate highways are designed as two-lane or multi-lane depending on the number of lanes required to handle their historical traffic load. If the historical traffic volume for a highway sample can be handled by a two-lane highway, then highway costs for this sample will be computed assuming a two-lane highway (one lane in each direction). Otherwise, highway costs for the sample will be computed assuming a multi-lane highway.

For interstate highways and multi-lane, non-interstate highways, we adjusted historical traffic volumes by correction factors that account for certain features of multi-lane traffic flow that are absent in single-lane traffic flow. We then computed the minimum number of lanes required in each direction to handle the adjusted traffic volumes. See Appendix G for details.

3.10 SHOULDER

Pavement thickness is assumed in this study to be the same for shoulders as for lanes. For shoulder width, we calculated average values by type of pavement (Table 3.16) from the 1998 Road Inventory File.

Table 3.16. Pavement shoulder width (both directions)

	Rigid	Flexible (IH)	Flexible (US/SH)	Flexible (FM)
Average shoulder width (ft.)	31	33	19	16

The prevalence of shoulders on flexible-pavement roads varies by road type and region (Table 3.17). For rigid pavements, the 1998 Road Inventory File revealed shoulders on 53.24 percent of the total pavement length in Texas.

Table 3.17. Percentage of lane-miles with a paved shoulder: Flexible-pavement roads

Region	Interstate	U.S./state	Farm-to-market
1	97.67	56.96	6.75
2	99.20	78.01	12.69
3	96.33	78.58	5.09
4	94.58	76.79	10.85
5	86.10	66.01	6.74

3.11 COST ESTIMATES

The process of computing a cost estimate for the construction of a section of pavement consists of several steps:

1. From ADTs, we computed the required number of lanes (see Section 3.7).
2. From the number of lanes, region, pavement type, and pavement length, we computed the paved shoulder area.
3. From the number of lanes and length of pavement, we computed the paved lane area.
4. From the paved lane area and the paved shoulder area, we computed the total paved area.
5. From ADTs, we also computed the expected number of applied ESALs.
6. From ESALs, we computed the cost per cubic yard (and thus the cost per square yard of surface) by pavement type.
7. From the total paved area above and the cost per square yard, we computed the total pavement cost.

3.12 THE VARIABLE-NUMBER-OF-LANES SCENARIO

In most HCA studies, traffic-related highway costs are mainly distributed according to pavement thickness requirements, without any consideration of highway capacity requirements. This assumes that the number of lanes needed for the grand coalition is the same as that for any vehicle coalitions because all vehicle classes use all lanes in any highway facility and share the benefits of multiple lanes. This is referred as the *fixed-number-of-lanes scenario*.

Heavy trailer trucks necessitate a thicker pavement construction and more frequent pavement rehabilitation and maintenance than automobiles. On the other hand, automobiles necessitate more lanes than trailer trucks. Hence, the number of lanes required for each coalition is different because the needed number of lanes for automobiles is different from those for trailer trucks. This scenario is referred as the *variable-number-of-lanes scenario*.

Therefore, for highway cost allocation, two scenarios (i.e., the fixed-number-of-lanes scenario and the variable-number-of-lanes scenario) are considered. In the fixed-number-of-lanes scenario, the proportional method using ESALs, the MIA, and the GM will be applied and the

GM (Villarreal, 1985) will be recommended, and a new approach for considering both traffic capacity and traffic loads is proposed for the variable-number-of-lanes scenario.

A new highway cost allocation method is developed by using the Aumann-Shapley value (A-S value) and Shapley value. The A-S value can be interpreted as an arithmetic average of the sum of the marginal costs along the possible including sequences for each player. In addition, the Shapley value can be defined as the average marginal cost contribution each player would make to the grand coalition if players were to be included in the grand coalition one at a time.

THE PROPOSED APPROACH

In this approach, pavement construction costs or rehabilitation and maintenance costs are allocated to each vehicle class proportionally by its traffic load and its traffic capacity. Hence, the cost responsibility to each vehicle class can be calculated as follows:

$$x_i(E_i, L_i) = E_i\, C_e + L_i\, C_l$$

where

$x_i(E_i, L_i)$: Cost allocated to vehicle class i

E_i : ESALs for vehicle class i

C_e : Cost per ESAL

L_i : Number of lanes assigned to vehicle class i

C_l: Cost per lane

Cost per ESALs (C_e) and cost per lane (C_l) can be calculated by the A-S value, and the number of lanes assigned to each vehicle class (L_i) is determined by the Shapley value. The details and an example are shown in Appendix K.

BASE LANES AND ADDITIONAL LANES

Two base lanes for interstate highways and one base lane for US, state highways, and for farm-to-market roads are assumed in this research. Additional numbers of lanes for each vehicle coalition are calculated by using the Highway Capacity Manual (TRB, 1997).

The costs for the base lanes as well as the minimum pavement thickness (needed to withstand the environmental impact) were allocated proportionally according to VMT values, whereas the costs of additional lanes are allocated by approach proposed in the previous section of this report. The costs for base lanes can be calculated by multiplying the values of parameter *a* in Table 3.6 and Table 3.10 by the number of base lanes. As an illustration, if there is one base lane and two additional lanes, as shown in Figure 3.4, then the gray-colored portion will be allocated by the proposed approach and the remaining portion will be allocated proportionally by VMT.

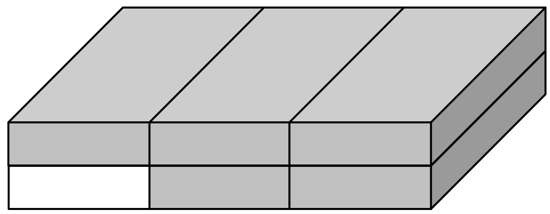


Figure 3.4. One base lane, two additional lanes, and additional pavement thickness

3.13 PAVEMENT COST ALLOCATION

Having developed all cost estimates, we applied five methods of setting cost responsibilities for the various vehicle classes.

We applied the generalized method to find a cost allocation for flexible and rigid pavement construction costs. For each combination of vehicle class, highway type, and geographic region, we collected from the Highway Classification Report as many as thirty ADT samples that matched that combination (see Appendix A). We then solved the linear programming problem provided by the generalized method using the commercially available solver CPLEX. The number of lanes calculated for each ADT samples are given in Appendix I. Actually, the costs for base facility are allocated proportionally by VMT, and other load-related pavement costs are allocated by the generalized method. If the generalized method yielded multiple optimal allocations, then a second phase of the generalized method was implemented. From among all the optimal allocations yielded by Phase 1, Phase 2 found the allocation for which cost responsibilities most nearly reflected the statistical effect that each vehicle class had on cost. See Appendix F for details.

TxDOT records of expenditures for pavement construction and pavement rehabilitation and maintenance do not distinguish between rigid pavement projects and flexible pavement projects. It is important, however, to make such a distinction in our cost allocation since the costs of these activities are quite different for the different pavement types.

To separate flexible and rigid pavement *construction* costs a sample of each type was considered for each region and highway type. The actual construction costs were estimated proportionally to the construction cost corresponding to a sample of highway sections. As an illustration, for Region 1 and IH flexible pavements, the existing total number of lane-miles is equal to 1,570,362. The sample for this region/highway type combination included 96 lane-miles with a total cost of $47,838,761. From this, we obtain an estimate of $47,838,761/96 = $498,320 per lane-mile. Using this estimate, it is possible estimate the total cost of constructing the entire number of lane-miles existing in the region as $498,320 x 1,570,362, or about $782 billion. Finally, the total cost actually spent on constructing flexible IH pavements in Region 1 was determined *proportionally* to this value.

For *rehabilitation* costs and *routine maintenance* costs that are common to flexible and rigid pavements, the existing lane-miles are used as a proportional allocator between these pavement types.

We then compared these results with results from the modified incremental approach (MIA), the proportional method by ESALs (Proportional (ESALs)), the proposed method for the variable-number-of-lanes scenario (variable), and from the FHWA software for State HCA (FHWA software). Table 3.18 displays pavement construction cost responsibility by vehicle class as calculated by these five methods of cost allocation. Details on the results are found in Appendix C. Appendix M summarizes relevant aspects of the procedure in the FHWA software.

Using the same data samples as were used for flexible pavement construction cost allocation, we applied the generalized method to the allocation of flexible pavement rehabilitation and maintenance costs. The second phase of the generalized method was never needed in these allocations because Phase 1 returned unique solutions in every case. Details are found in Appendix C.

Rigid pavement rehabilitation and maintenance costs were allocated proportionally by ESALs. Table 3.19 shows pavement rehabilitation and maintenance cost responsibilities by vehicle class, as calculated by five different methods of cost allocation. Details are found in Appendix C. These methods except the FHWA software use the AASHTO's fourth power law, which states that pavement deterioration is proportional to the fourth power of axle load. The FHWA software procedure for pavement rehabilitation and maintenance, on the other hand, uses the Nationwide Pavement Cost Model (NAPCOM) which assumes a third power of axle load instead of the fourth power. As a result of this difference, the FHWA software allocates a larger share of costs to heavy vehicle classes than do the other methods.

Bridge construction costs were allocated by the MIA (Appendix H), which is equivalent to the current FHWA approach for allocating these costs. Table 3.20 gives the resulting breakdown of cost responsibility by vehicle class.

Simplest of all was the allocation of common costs. They were distributed in proportion to each vehicle class's VMT, for which the percentage distribution is shown in Table 3.21.

Table 3.18. Load-related pavement construction cost by vehicle class, Texas 1998: Percent distributions according to method of allocation

	GM	MIA	Proportional (ESALs)	Variable	FHWA Software
Auto	29.60	29.22	5.36	30.11	23.25
Pickup	10.56	11.15	2.36	11.93	11.27
Other 2 Ax SU	4.03	6.10	7.22	5.08	7.63
3 Ax SU	3.19	3.94	7.41	4.36	5.31
4 Ax+ SU	0.21	0.15	0.49	0.81	0.84
4 Ax– STT	1.85	2.18	3.93	2.95	2.58
5 Ax STT	47.07	43.82	64.88	38.02	44.37
6 Ax+ STT	0.61	0.57	1.49	1.51	1.27
5 Ax– MTT	1.32	1.37	2.44	2.19	0.95
6 Ax MTT	0.19	0.13	0.28	0.64	0.08
7 Ax+ MTT	0.08	0.01	0.03	0.11	0.04
Bus	1.29	1.37	4.11	2.29	2.42
Total	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**

Table 3.19. Pavement rehabilitation and maintenance cost by vehicle class, Texas 1998: Percent distributions according to method of allocation[a]

	GM	MIA	Proportional (ESALs)	Variable	FHWA software
Auto	1.87	1.87	0.68	7.33	12.37
Pickup	0.91	0.91	0.36	2.54	6.22
Other 2 Ax SU	4.84	4.84	4.94	4.70	6.60
3 Ax SU	6.59	6.59	6.77	5.99	6.84
4 Ax+ SU	0.35	0.35	0.37	0.64	1.88
4 Ax– STT	3.57	3.57	3.65	3.57	2.28
5 Ax STT	74.33	74.33	75.49	66.99	58.52
6 Ax+ STT	1.39	1.38	1.42	1.67	1.85
5 Ax– MTT	3.35	3.35	3.38	3.37	0.71
6 Ax MTT	0.32	0.32	0.32	0.59	0.06
7 Ax+ MTT	0.03	0.03	0.03	0.08	0.07
Bus	2.46	2.46	2.57	2.53	2.61
Total	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**

a The method of allocation varies only for flexible pavements; Rigid pavement costs were allocated proportionally by ESALs in each case.

Table 3.20. Bridge cost responsibilities by vehicle class, Texas 1998, percent distribution

Vehicle class	Cost Percentage
Auto	51.47
Pickup	16.08
Other 2 Ax SU	3.28
3 Ax SU	1.23
4 Ax+ SU	0.14
4 Ax– STT	1.12
5 Ax STT	21.56
6 Ax+ STT	2.79
5 Ax– MTT	0.82
6 Ax MTT	0.35
7 Ax+ MTT	0.62
Bus	0.54
Total	**100.00**

Table 3.21. VMT by vehicle class, Texas 1998, percent distribution

Vehicle class	Percentage of total VMTs
Auto	67.79
Pickup	21.06
Other 2 Ax SU	3.65
3 Ax SU	0.86
4 Ax+ SU	0.03
4 Ax– STT	0.61
5 Ax STT	5.28
6 Ax+ STT	0.12
5 Ax– MTT	0.20
6 Ax MTT	0.03
7 Ax+ MTT	0.01
Bus	0.36
Total	**100.00**

3.14 COST SUMMARY

Table 3.22 gives a breakdown of highway construction and maintenance costs based on data from TxDOT. Load-related pavement construction costs include load-related pavement costs from bridge construction projects. See Appendices B and E for details.

Table 3.22. Highway costs by component, Texas 1998

	$ thousand	**%**
Load-related pavement construction costs	804,651	25.36
Load-related flexible pavement rehabilitation and maintenance costs	560,510	17.67
Load-related rigid pavement rehabilitation and maintenance costs	34,327	1.08
Bridge costs	171,866	5.42
Common costs	**1,601,575**	**50.48**
Total Cost	**3,172,929**	**100.00**

As stated above, five allocation methods were used to allocate flexible and rigid pavement construction costs and flexible pavement rehabilitation and maintenance costs. In all cases, common costs were allocated proportionally by VMT, rigid pavement rehabilitation and maintenance costs were allocated proportionally by ESALs, and bridge costs were allocated by the MIA. The responsibilities for these cost components were combined using the percentages in Table 3.22 to arrive at a total cost responsibility for each vehicle class.

As stated in the material on cost allocation issues, we endorse methods that maintain the principles of rationality and marginality. We believe that the two-phase generalized method best maintains these principles in the allocation of pavement construction costs and flexible pavement rehabilitation costs.

Table 3.23 gives a percentage breakdown of total cost responsibilities. The column headings indicate the method used to allocate pavement construction costs and flexible pavement rehabilitation and maintenance costs.

Table 3.23. Total cost responsibility by vehicle class, Texas 1998: Percent distributions according to method of allocation

	GM	MIA	Proportional (ESALs)	Variable	FHWA software
Auto	44.86	44.77	38.49	46.02	45.22
Pickup	14.35	14.50	12.17	15.00	15.53
Other 2 Ax SU	3.95	4.47	4.78	4.19	5.19
3 Ax SU	2.54	2.73	3.65	2.73	3.13
4 Ax+ SU	0.14	0.12	0.21	0.35	0.58
4 Ax– STT	1.51	1.59	2.05	1.79	1.45
5 Ax STT	29.71	28.88	34.44	26.04	26.06
6 Ax+ STT	0.62	0.61	0.85	0.90	0.88
5 Ax– MTT	1.11	1.12	1.40	1.33	0.52
6 Ax MTT	0.14	0.13	0.17	0.31	0.07
7 Ax+ MTT	0.06	0.05	0.05	0.08	0.06
Bus	1.00	1.02	1.74	1.27	1.31
Total	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**

4. EQUITY ANALYSIS

The equity ratios combine the results of our revenue and cost allocation analyses. For each class, the equity ratio equals its share of highway-related tax revenues divided by its share of highway-related costs. When equity ratios are below unity for some classes, then, of algebraic necessity, they must exceed unity for some other classes.

The equity ratios differ only slightly between our two approaches to revenue allocation. Some revenues collected from highway users are not dedicated to highway spending, but whether our estimates include them (Table 4.1) or exclude them (Table 4.2) barely affects the results. Since our preferred approach is to include such revenues, the rest of this discussion focuses on the equity ratios obtained with this approach. Table 4.3 presents these ratios for passenger cars, buses, and an aggregation of our ten truck classes.

If an equity ratio of unity is the benchmark of fairness, classes with equity ratios greater than unity are paying more than their fair share of Texas highway system costs. These classes are cross-subsidizing the other vehicle classes, which have equity ratios less than unity.

Applied to the results in Table 4.3, this criterion of fairness would lead to the conclusion that light vehicles—autos and particularly pickup trucks—are cross-subsidizing combination trucks and buses. Although the results vary somewhat among the allocation methods—none of which are unambiguously superior to the others—each method produces this same pattern. For single-unit trucks excluding pickups, the equity ratios provide no clear indication that they are paying anything other than their fair share

The sensitivity of the results to the allocation method is more pronounced at the 12-vehicle class level (Table 4.1). A caveat to the detailed results is that they are likely less reliable for the less common vehicle classes. The least common classes are multi-trailer trucks with seven or more axles, followed by single-unit trucks with four or more axles: they each account for less than four out of every 10,000 miles traveled on Texas roads (Table 3.16). For such classes, the sample sizes in transportation data collections will often be smaller, and hence the estimates less reliable, than those for the more common vehicle classes. For example, the Texas WIM data included no observations for the two classes just mentioned, so we had to measure their operating weights from national-level data (Appendix N).

The low ratios for buses stem in part from the many tax exemptions and preferences they receive. Changes in our assumptions about the mileage and type of fuel consumed by private buses do not readily alter this pattern. Our sensitivity analysis of these assumptions produced a range of estimates of the bus share of tax revenues. But even the highest of these estimates is less than the estimated bus share of highway system costs. On the extreme assumption that private buses average 50,600 miles annually, the estimated bus share of tax revenues increased to 0.77 percent. In comparison, our estimates of the bus share of highway system costs range from 1.00 percent to 1.74 percent (Table 3.23).

Table 4.1. Equity ratios using alternative allocation methods and including all revenues, Texas 1998

	GM	MIA	Proportional (ESALs)	Variable	FHWA software
Auto	1.15	1.15	1.34	1.12	1.16
Pickup	1.47	1.45	1.73	1.40	1.35
Other 2 Ax SU	1.26	1.11	1.04	1.19	0.94
3 Ax SU	0.73	0.68	0.51	0.68	0.75
4 Ax+ SU	0.62	0.71	0.41	0.25	0.18
4 Ax– STT	1.02	0.96	0.75	0.86	1.13
5 Ax STT	0.58	0.60	0.50	0.67	0.62
6 Ax+ STT	0.65	0.66	0.48	0.45	0.44
5 Ax– MTT	0.55	0.55	0.44	0.46	1.18
6 Ax MTT	0.72	0.81	0.61	0.33	1.51
7 Ax+ MTT	0.26	0.36	0.33	0.21	0.26
Bus	0.41	0.40	0.23	0.32	0.30

Note: The results for the FHWA software procedure are based on the revenue shares in table 2.10. The results in the other columns are based on the revenue shares in table 2.4.

Table 4.2. Equity ratios using alternative allocation methods and excluding revenues not dedicated to highways, Texas 1998

	GM	MIA	Proportional (ESALs)	Variable	FHWA software
Auto	1.13	1.13	1.32	1.10	1.13
Pickup	1.46	1.44	1.72	1.39	1.35
Other 2 Ax SU	1.25	1.11	1.04	1.18	0.93
3 Ax SU	0.78	0.73	0.55	0.73	0.79
4 Ax+ SU	0.68	0.78	0.45	0.28	0.19
4 Ax– STT	1.07	1.02	0.79	0.90	1.18
5 Ax STT	0.61	0.63	0.53	0.70	0.66
6 Ax+ STT	0.69	0.70	0.51	0.48	0.47
5 Ax– MTT	0.58	0.57	0.46	0.48	1.24
6 Ax MTT	0.76	0.85	0.64	0.35	1.58
7 Ax+ MTT	0.28	0.38	0.35	0.22	0.27
Bus	0.39	0.39	0.23	0.31	0.29

Note: The results for the FHWA software procedure are based on the revenue shares in table 2.10. The results in the other columns are based on the revenue shares in table 2.4.

Table 4.3. Equity ratios by broad vehicle class including all revenues, Texas 1998

	GM	MIA	Proportional (ESALs)	Variable	FHWA software
Auto	1.15	1.15	1.34	1.12	1.16
Pickup	1.47	1.45	1.73	1.40	1.35
Other Single-Unit trucks	1.04	0.94	0.80	0.95	0.82
Combination Trucks	0.60	0.62	0.51	0.66	0.65
Buses	0.41	0.40	0.23	0.32	0.30

4.1 COMPARISONS WITH OTHER STUDIES

The equity ratios from the previous Texas HCA study (Euritt et al. 1994) allow comparison with those obtained in the current study, since the differences in the vehicle classification were minor. For the detailed truck classes, some differences in the equity ratios are noticeable. But at a more aggregate level, the similarities are much more striking than the differences. If an equity ratio of unity is considered fair, both sets of results imply that combination trucks and buses are paying less than their fair share, at the expense of passenger cars and pickup trucks.

Stowers et al. (1999) compared the equity ratios for "heavy vehicles" from twenty-three state HCA studies. All the studies were conducted after last major overhaul, in 1982, of federal standards for truck size and weight. The large amount of variation among the studies' equity ratios, from less than 0.60 in four studies to more than 1.0 in seven, could have stemmed partly from the lack of a consistent definition of "heavy vehicle." Other contributing factors would include differences between studies in scope and methods, and differences between states in taxation regimes and road network characteristics.

Table 4.4. Equity analysis for 1993 in previous Texas HCA study

Vehicle Class	% of Revenues (Federal and State)	% of Costs	Equity Ratio
Auto	48.87	38.23	1.28
Pickup	23.99	12.42	1.93
Other Single-Unit Trucks	8.26	8.44	0.98
2 axle	5.19	5.81	0.89
3 or more axle	3.07	2.63	1.17
Combinations	18.21	39.22	0.46
3 axle single trailer	0.14	1.24	0.12
4 axle single trailer	0.32	2.33	0.14
5 axle single trailer	16.11	31.48	0.51
6 axle single trailer	0.50	1.36	0.37
5 axle twin trailer	0.97	1.97	0.49
6 axle twin trailer	0.17	0.84	0.21
Buses	0.67	1.69%	0.40
2 axle	0.48	0.88%	0.55
3 axle	0.19	0.81%	0.24
Total	100.00	100.00	1.00

Source: Euritt (1994, p. 39)

5. DIRECTIONS FOR FUTURE RESEARCH

5.1 FUNDAMENTAL SHIFTS IN DIRECTION

A well-done HCA study informs public decision-making on road user taxes. Are different classes of vehicles paying their fair share of these taxes? An HCA study can shed light on that question, which figures prominently in political debates over highway financing.

But HCA studies leave aside some other important questions about the appropriate package of road user taxes. How would a change in the current package affect the environment? When oil prices increase, there can be pressure on governments to reduce taxes on motor fuels. If a government were to yield to this pressure, the resulting stimulus to consumption of motor fuels could compromise air quality. Estimating the potential deterioration in air quality, and perhaps assigning it a cost, would help evaluate such a move.

One would also want to know how a change to road user taxes would affect traffic congestion, a growing concern in Texas cities. What if Texas were to increase the currently minor concession on diesel fuel tax for transit buses? Such a reform would make the equity ratios in an HCA study look less fair, but it would also induce some expansion in bus transit services. Some car travelers would switch to taking the bus, which, one would hope, would relieve traffic congestion and air pollution. But rather than building a policy on hope, one would want to estimate these effects beforehand.

Then there is the question of how road user taxes affect the economy. As was noted earlier, Texas taxes diesel fuel and gasoline at the same per gallon rate. If Texas were to increase the rate on diesel fuel and reduce the rate on gasoline while keeping the total tax revenue constant, how would the Texas economy fare? The scenario is not purely academic, as the federal government has already built this sort of differential into its fuel taxes. It is one of many reform scenarios for road user taxes on which a suitable model of the state economy could throw light. For an idea of how such modeling might be conducted, see Swan Consultants (1994).

Finally, the distribution of the tax burden between vehicle classes is only one dimension on which the fairness of road user taxes can be judged. One could also look at broader aspects of social justice, such as the burden of these taxes on low-income or otherwise disadvantaged groups. After all, why are the Texas registration fees lower for older cars than for newer ones? Presumably, because the newer cars have more affluent owners who can more easily afford the fees. Some other states have registration fees that are even more egalitarian, being based on the car's value.

In our view, a comprehensive evaluation of the system of road user taxes in Texas would be highly desirable. The evaluation would supplement the framework developed for this project with other analytical frameworks, in order to answers to some of the broader questions discussed above. In addition, Texas should conduct a Highway Cost Allocation study every five years to coincide with the release of data from the most recent Vehicle Inventory and Use Survey.

Provided that the requisite data are available, the next study should go beyond this study's focus on state-maintained roads, to consider the costs and revenues associated with use of local roads. Before the next Texas HCA study, however, we hope to see applications of the present framework to simulate the effects of potential tax reforms.

5.2 MODIFICATIONS TO COST ANALYSIS

To enhance certain features of our cost allocation framework, we also recommend two other directions for research.

First, the allocation of traffic-related pavement costs could stand improvement. The usual practice in HCA studies, mostly followed in this study as well, is to allocate these costs based on traffic loads only (ESALs). But the allocation should also take account of traffic capacity, since traffic-related pavement costs increase with additional lanes. Estimation of a capacity level for each vehicle, or group of vehicles, would entail a lane assignment procedure in conjunction with the highway capacity manual. The present study included a nominal effort, not based on the Generalized Method, to separate traffic load costs from traffic capacity costs. A more comprehensive analysis should investigate possible utilization of the Generalized Method, the results of which could be compared with those from the approach used in the study.

Second, the allocation of bridge costs calls for an approach that would consider both traffic loading and traffic capacity, unlike the approach used in this study (the MIA), which assumes a fixed number of lanes. On bridges, gross vehicle weights are more important than vehicle passes, so gross vehicle weights measure traffic loadings much better than do ESALs. Hence, the maximum gross vehicle weight in each weight group (e.g.. 5 kips, 10 kips, etc.) plays a role in the traffic separation problem, as does the number of lanes. Solving this separation problem would determine the cost for each additional lane and for each maximum gross vehicle weight; this, in turn, would allow implementation of the envisaged new approach to allocating bridge costs.

APPENDIX A. HIGHWAY SECTION SAMPLES

For each combination of geographic region and highway type, we selected flexible-pavement highway sections from which to collect ADT data for each vehicle class. The data were taken from the TxDOT *1998 Vehicle Classification Report*.

Table A.1. Highway sections by road type for Region 1

IH	District 10	M1960
	District 12	HP845, HP849, HP850, HP851, HP852, HP853, HP854, HP856, HP857, HP859, HP860, HP864, HP865, M1200, MA316, MS125, MS204
	District 19	HP953, M1065, M1940, M1941, MS150, MS199
	District 20	HP961, HP964, M1216, M1253, M1499, MS117
US/SH	District 1	LX102, M500, M1068
	District 10	HP839, LX1012, LX1013
	District 11	L72, M921, M922, M923, M1035, M1036
	District 12	HP841, HP842, HP843, HP846, HP847, HP848
	District 19	HP947, HP949, LX1924, LX1925, M930, M1031
	District 20	HP958, HP963, LX2026, LX2027, LX2028, M1038
FM	District 11	M1229
	District 12	HP861, HP863
	District 19	HP948
	District 20	HP960, HP962, MS86

Table A.2. Highway sections by road type for Region 2

IH	District 6	M178, M1660, MS195
	District 7	MS14, MS217
	District 8	HP830, LW504, M1760, LW519, MA325, MS153
	District 24	HP973, HP975, LW510, HP974, M1680, MS152, MT680, MS162
US/SH	District 6	LX607, M176, M882, M1100, M1101, M1102, M1184, M1185
	District 7	HP825, M724, M943, M955, M1002, M1003, M1103
	District 8	MS23, M1278, M1277, M1276, M1275, M1108, M1107, M1106, M1105
	District 24	HP972, LX2433, M10, M1165, M1166, MS7
FM	District 24	BC2401, BC2406

Table A.3. Highway sections by road type for Region 3

IH	District 4	LW520, U11
	District 5	M1223
US/SH	District 4	LX401, M1013, M1078, M1079, M1080, M1081, M1093, M1094, M1261, M1261, MS120
	District 5	HP821, HP822, M951, M1007, M1084, M1085, M1096, M1221, M1222, M1263, M1265
	District 25	M950, M1015, M1169, M1170, M1172, M1301, M1302, MS24
FM	District 5	LX501

Table A.4. Highway sections by road type for Region 4

IH	District 13	HP869, MS164
	District 15	HP879, HP880, HP881, HP883, HP884, HP885, HP886, HP889, HP890, L102, LW516, LW518, M1246, M1315, M1620, M1621, M1622, M1623, M1624
	District 16	LW512, M1243, MS54
	District 22	M1601, M1602, M1603, MA308, MT420, BC2206
US/SH	District 13	HP868, M912, M913, M914, M1052, M1123, M1124, M1125, M1201, M1204
	District 15	M905, M1232
	District 16	HP892, LX1620, M778, M1133, M1134, M1136, M1137, M1244
	District 21	HP965, HP967, LW515, LX2130, M1046, M1239
	District 22	L147, LX1519, M907, M956
FM	District 13	M1203
	District 16	MS91
	District 21	BC2103, BC2104, BC2107, M1241
	District 22	BC2205, M1604

Table A.5. Highway sections by road type for Region 5

IH	District 2	HP803, HP804, L30, L202, M1257, MS192, MS193
	District 3	HP816, M1072, M1800, MS167
	District 9	HP831, HP835, LW513, M1112, MS197
	District 14	HP870, HP871, HP877, HP878, LW508, M1860, MS4, MS132
	District 17	LW507
	District 18	HP933, HP934, HP936, LW514, M1149
US/SH	District 2	HP805, HP806, HP811, HP813, HP814
	District 3	HP817, L20, LW506, M278, M945
	District 9	HP834, HP836, HP837, M1022
	District 14	HP872, HP873, HP874, HP875
	District 17	LX1722, LX1723, M675, M939
	District 18	HP895, HP938, M1151, MS55
	District 23	HP970, HP971, L7, LX2332
FM	District 2	M1258
	District 9	HP838
	District 14	M1289
	District 23	M1297

For each combination of geographic region and highway type, we selected rigid-pavement highway sections from which to collect ADT data for each vehicle class. The data were taken from the TxDOT *1998 Vehicle Classification Report*.

Table A.6. Highway sections by road type for the Houston area

IH	HP844, HP845, HP849, HP850, HP851
US/SH	HP841, HP842, HP843, HP846, HP847
FM	HP861, HP863

Table A.7. Highway sections by road type for other areas

Region 1	IH	M1499, MS117
	US/SH	LX102, M500
	FM	HP948, HP960
Region 2	IH	HP830, HP973
	US/SH	M1107, M1108
	FM	BC2401, BC2406
Region 3	IH	LW520, U11
	US/SH	LX401, M1013
	FM	LX501
Region 4	IH	HP869
	US/SH	None
	FM	M1203
Region 5	IH	HP803, HP816, HP804
	US/SH	HP817, L20
	FM	M1258

APPENDIX B. CALCULATION OF COMMON COSTS

The following sums give breakdowns of pavement construction costs, total construction costs, and total highway costs:

Load-related pavement construction costs in construction projects	$ 576,929,357
Load-related pavement cost estimates in bridge projects	$ 122,457,264
Total pavement construction costs	$ 699,386,622

Total load-related pavement construction costs	$ 699,386,622
Load-related pavement rehabilitation costs	$ 263,482,374
Load-related pavement preventive maintenance costs	$ 72,979,366
Bridge costs	$ 153,959,665
Other rehabilitation and construction costs	$ 928,102,974
Total construction letting volumes	$2,117,911,000

Total construction letting volumes	$2,117,911,000
Load-related costs in routine maintenance projects	$ 241,131,074
Bridge costs in routine maintenance projects	$ 17,906,176
Non-load related costs in routine maintenance projects	$ 348,192,595
Load-related preliminary & construction engineering costs in construction projects	$ 105,264,716
Load-related preliminary & construction engineering costs in rehabilitation projects	$ 12,439,766
Load-related preliminary & construction engineering costs in preventive maintenance projects	$ 4,804,614
Nonload-related costs in preliminary & construction engineering	$ 183,763,644
Right-of-way costs	$ 141,515,665
Total costs	$3,172,929,250

Total common costs are found with the following calculation:

Total common costs = Total costs – Load-related pavement and bridge costs
= Other rehabilitation and construction costs
+ Non-load-related costs in routine maintenance projects
+ Non-load-related preliminary & construction engineering costs
+ Right-of-way costs
= $ 928,102,974
$ 348,192,595
$ 183,763,644
+) $ 141,515,665
$1,601,574,879

As a percentage of total costs, common costs are

$$100\times(1{,}601{,}574{,}879 \div 3{,}172{,}929{,}250) = 50.48 \text{ percent.}$$

APPENDIX C. COST RESPONSIBILITIES

Throughout this appendix, methods will be abbreviated as follows: “GM” for generalized method; “MIA” for modified incremental approach; “Proportional (ESALs)” for proportional method by ESALs; and “Variable” for the proposed method in the variable-number-of-lanes scenario. Each table includes cost responsibilities as determined by each of these methods.

The following tables give cost responsibilities for load-related rigid pavement construction costs by each combination of region and vehicle class.

Table C.1. Rigid pavement construction cost responsibilities by method for the Houston area

	GM	MIA	Proportional (ESALs)	Variable
Auto	45.32	45.32	6.89	49.06
Pickup	9.19	9.58	1.57	12.21
Other 2 Ax SU	3.10	5.20	5.19	3.98
3 Ax SU	2.54	3.33	7.37	3.26
4 Ax+ SU	0.34	0.16	0.55	1.13
4 Ax– STT	1.03	1.09	2.43	1.85
5 Ax STT	35.42	32.82	68.81	22.10
6 Ax+ STT	0.65	0.50	1.58	1.46
5 Ax– MTT	0.74	0.62	1.73	1.55
6 Ax MTT	0.20	0.03	0.08	0.88
7 Ax+ MTT	0.19	0.01	0.05	0.38
Bus	1.28	1.33	3.76	2.14

Table C.2. Rigid pavement construction cost responsibilities by method for other areas

	GM	MIA	Proportional (ESALs)	Variable
Auto	35.70	35.63	11.56	34.41
Pickup	14.67	14.81	5.31	15.51
Other 2 Ax SU	3.32	3.81	3.96	4.35
3 Ax SU	1.93	2.16	4.55	2.93
4 Ax+ SU	0.21	0.11	0.28	0.68
4 Ax– STT	1.44	1.51	2.02	2.24
5 Ax STT	39.86	39.41	65.93	33.91
6 Ax+ STT	0.53	0.45	1.08	1.32
5 Ax– MTT	1.22	1.26	2.24	1.98
6 Ax MTT	0.27	0.17	0.49	0.90
7 Ax+ MTT	0.12	0.01	0.02	0.25
Bus	0.74	0.67	2.56	1.52

The following tables give cost responsibilities for load-related flexible pavement construction costs by each combination of region, highway type, and vehicle class.

Table C.3. Flexible pavement construction cost responsibilities by method for Region 1 interstate highways

	GM	MIA	Proportional (ESALs)	Variable
Auto	14.30	14.11	3.59	15.93
Pickup	3.37	3.97	1.11	4.05
Other 2 Ax SU	2.91	5.06	3.99	3.67
3 Ax SU	3.05	3.71	4.89	3.99
4 Ax+ SU	0.35	0.09	0.16	0.63
4 Ax– STT	1.55	1.57	2.19	2.11
5 Ax STT	69.15	66.98	77.37	62.22
6 Ax+ STT	0.90	0.68	1.11	1.35
5 Ax– MTT	2.22	2.17	3.14	3.14
6 Ax MTT	0.44	0.18	0.27	0.67
7 Ax+ MTT	0.27	0.02	0.03	0.22
Bus	1.47	1.45	2.15	2.01

Table C.4. Flexible pavement construction cost responsibilities by method for Region 1 U.S. and state highways

	GM	MIA	Proportional (ESALs)	Variable
Auto	21.18	20.68	3.82	27.64
Pickup	5.36	6.23	1.40	8.18
Other 2 Ax SU	3.55	6.98	5.57	4.70
3 Ax SU	3.83	5.16	7.15	5.08
4 Ax+ SU	0.29	0.18	0.36	0.73
4 Ax– STT	1.72	2.03	3.12	2.63
5 Ax STT	60.15	54.92	71.73	44.16
6 Ax+ STT	0.76	0.68	1.28	1.58
5 Ax– MTT	1.08	1.06	1.94	1.90
6 Ax MTT	0.15	0.04	0.08	0.61
7 Ax+ MTT	0.12	0.01	0.02	0.16
Bus	1.80	2.02	3.52	2.63

Table C.5. Flexible pavement construction cost responsibilities by method for Region 1 farm-to-market roads

	GM	MIA	Proportional (ESALs)	Variable
Auto	50.96	50.96	2.54	43.26
Pickup	17.03	17.03	1.24	15.46
Other 2 Ax SU	7.07	7.40	15.30	7.22
3 Ax SU	5.11	5.10	16.56	6.46
4 Ax+ SU	0.02	0.02	0.60	0.96
4 Ax– STT	0.69	0.54	4.23	3.06
5 Ax STT	15.51	15.91	44.41	14.62
6 Ax+ STT	0.07	0.07	2.10	2.00
5 Ax– MTT	2.16	1.79	4.83	2.94
6 Ax MTT	0.00	0.00	0.02	0.19
7 Ax+ MTT	0.00	0.00	0.00	0.00
Bus	1.39	1.17	8.17	3.82

Table C.6. Flexible pavement construction cost responsibilities by method for Region 2 interstate highways

	GM	MIA	Proportional (ESALs)	Variable
Auto	10.08	9.80	2.80	10.77
Pickup	2.66	2.93	0.98	3.00
Other 2 Ax SU	2.30	2.93	2.20	2.44
3 Ax SU	2.31	2.79	3.43	2.99
4 Ax+ SU	0.26	0.07	0.11	0.39
4 Ax– STT	2.73	3.37	3.57	3.60
5 Ax STT	72.59	71.20	77.52	67.29
6 Ax+ STT	0.90	0.76	1.09	1.24
5 Ax– MTT	3.97	4.32	5.86	5.37
6 Ax MTT	0.80	0.66	0.87	1.11
7 Ax+ MTT	0.27	0.08	0.12	0.28
Bus	1.13	1.09	1.47	1.52

Table C.7. Flexible pavement construction cost responsibilities by method for Region 2 U.S. and state highways

	GM	MIA	Proportional (ESALs)	Variable
Auto	22.53	22.15	7.54	21.83
Pickup	15.68	16.48	6.02	15.60
Other 2 Ax SU	6.97	9.40	7.85	7.76
3 Ax SU	2.83	3.14	5.15	3.62
4 Ax+ SU	0.34	0.35	0.67	0.53
4 Ax– STT	4.00	4.82	6.96	5.17
5 Ax STT	42.39	37.96	55.47	38.36
6 Ax+ STT	2.06	2.09	3.72	2.70
5 Ax– MTT	0.36	0.38	0.70	0.58
6 Ax MTT	0.09	0.09	0.16	0.23
7 Ax+ MTT	0.22	0.23	0.47	0.37
Bus	2.54	2.91	5.28	3.24

Table C.8. Flexible pavement construction cost responsibilities by method for Region 2 farm-to-market roads

	GM	MIA	Proportional (ESALs)	Variable
Auto	71.33	71.33	11.94	71.33
Pickup	27.10	27.10	7.08	27.10
Other 2 Ax SU	1.07	1.07	23.98	1.07
3 Ax SU	0.10	0.10	9.68	0.10
4 Ax+ SU	0.00	0.00	0.00	0.00
4 Ax– STT	0.04	0.04	4.46	0.04
5 Ax STT	0.02	0.02	3.43	0.02
6 Ax+ STT	0.00	0.00	0.00	0.00
5 Ax– MTT	0.00	0.00	0.00	0.00
6 Ax MTT	0.06	0.06	8.24	0.06
7 Ax+ MTT	0.00	0.00	0.00	0.00
Bus	0.29	0.29	31.19	0.29

Table C.9. Flexible pavement construction cost responsibilities by method for Region 3 interstate highways

	GM	MIA	Proportional (ESALs)	Variable
Auto	10.10	9.76	3.02	8.51
Pickup	2.83	3.17	1.06	3.69
Other 2 Ax SU	2.00	3.11	2.25	2.68
3 Ax SU	1.34	1.40	1.80	1.95
4 Ax+ SU	0.40	0.27	0.37	0.67
4 Ax– STT	1.75	2.05	2.28	2.47
5 Ax STT	77.36	76.48	83.85	73.82
6 Ax+ STT	0.59	0.45	0.68	0.94
5 Ax– MTT	2.39	2.48	3.54	3.39
6 Ax MTT	0.33	0.17	0.26	0.57
7 Ax+ MTT	0.17	0.01	0.02	0.17
Bus	0.73	0.64	0.86	1.12

Table C.10. Flexible pavement construction cost responsibilities by method for Region 3 U.S. and state highways

	GM	MIA	Proportional (ESALs)	Variable
Auto	13.75	13.24	4.35	13.28
Pickup	9.02	9.67	3.35	9.76
Other 2 Ax SU	3.05	4.54	3.32	4.10
3 Ax SU	1.90	2.19	2.98	2.79
4 Ax+ SU	0.34	0.30	0.48	0.64
4 Ax– STT	3.47	4.34	5.14	4.67
5 Ax STT	63.87	60.88	73.12	57.61
6 Ax+ STT	1.10	1.13	1.80	1.73
5 Ax– MTT	1.83	2.03	2.95	2.63
6 Ax MTT	0.33	0.29	0.42	0.71
7 Ax+ MTT	0.07	0.00	0.01	0.10
Bus	1.26	1.39	2.08	1.98

Table C.11. Flexible pavement construction cost responsibilities by method for Region 3 farm-to-market roads

	GM	MIA	Proportional (ESALs)	Variable
Auto	23.44	23.44	0.82	23.25
Pickup	25.32	25.32	0.95	25.15
Other 2 Ax SU	3.92	3.92	2.48	4.48
3 Ax SU	8.35	8.35	21.72	13.60
4 Ax+ SU	0.12	0.12	0.56	0.26
4 Ax– STT	3.14	3.14	7.44	4.93
5 Ax STT	35.33	35.33	64.09	27.49
6 Ax+ STT	0.37	0.37	1.94	0.85
5 Ax– MTT	0.00	0.00	0.00	0.00
6 Ax MTT	0.00	0.00	0.00	0.00
7 Ax+ MTT	0.00	0.00	0.00	0.00
Bus	0.00	0.00	0.00	0.00

Table C.12. Flexible pavement construction cost responsibilities by method for Region 4 interstate highways

	GM	MIA	Proportional (ESALs)	Variable
Auto	13.22	12.60	3.89	11.45
Pickup	3.53	4.25	1.42	3.87
Other 2 Ax SU	2.72	4.69	3.76	3.70
3 Ax SU	3.91	5.11	6.08	5.41
4 Ax+ SU	0.11	0.07	0.11	0.30
4 Ax– STT	1.47	1.72	2.24	2.14
5 Ax STT	70.99	67.33	76.41	67.03
6 Ax+ STT	0.50	0.47	0.71	0.85
5 Ax– MTT	1.67	1.75	2.53	2.42
6 Ax MTT	0.27	0.24	0.35	0.55
7 Ax+ MTT	0.06	0.02	0.03	0.06
Bus	1.54	1.76	2.48	2.23

Table C.13. Flexible pavement construction cost responsibilities by method for Region 4 U.S. and state highways

	GM	MIA	Proportional (ESALs)	Variable
Auto	19.14	18.52	5.43	19.19
Pickup	9.32	10.38	3.28	11.34
Other 2 Ax SU	4.26	6.66	5.53	5.49
3 Ax SU	2.42	2.91	4.38	3.44
4 Ax+ SU	0.39	0.39	0.72	1.14
4 Ax– STT	2.86	3.56	4.90	4.20
5 Ax STT	57.93	53.55	69.05	48.11
6 Ax+ STT	1.20	1.29	2.21	2.17
5 Ax– MTT	0.71	0.75	1.24	1.52
6 Ax MTT	0.14	0.13	0.23	0.75
7 Ax+ MTT	0.02	0.01	0.01	0.01
Bus	1.60	1.85	3.03	2.65

Table C.14. Flexible pavement construction cost responsibilities by method for Region 4 farm-to-market roads

	GM	MIA	Proportional (ESALs)	Variable
Auto	42.66	42.66	2.67	39.67
Pickup	20.82	20.82	1.57	19.11
Other 2 Ax SU	3.22	3.22	6.51	4.45
3 Ax SU	4.60	4.46	10.66	4.64
4 Ax+ SU	0.06	0.06	0.56	0.83
4 Ax– STT	0.87	0.87	3.77	2.09
5 Ax STT	26.95	27.09	68.24	25.72
6 Ax+ STT	0.32	0.32	2.79	1.47
5 Ax– MTT	0.00	0.00	0.05	0.24
6 Ax MTT	0.00	0.00	0.03	0.23
7 Ax+ MTT	0.00	0.00	0.00	0.00
Bus	0.50	0.50	3.15	1.57

Table C.15. Flexible pavement construction cost responsibilities by method for Region 5 interstate highways

	GM	MIA	Proportional (ESALs)	Variable
Auto	13.56	13.17	3.80	11.96
Pickup	3.37	3.88	1.18	3.62
Other 2 Ax SU	2.23	3.64	2.74	3.01
3 Ax SU	2.11	2.48	3.19	3.00
4 Ax+ SU	0.23	0.09	0.14	0.42
4 Ax– STT	1.60	1.82	2.30	2.32
5 Ax STT	71.91	70.22	79.75	68.32
6 Ax+ STT	0.63	0.50	0.78	0.99
5 Ax– MTT	2.85	3.03	4.40	4.11
6 Ax MTT	0.51	0.38	0.58	0.84
7 Ax+ MTT	0.16	0.01	0.01	0.13
Bus	0.84	0.79	1.11	1.28

Table C.16. Flexible pavement construction cost responsibilities by method for Region 5 U.S. and state highways

	GM	MIA	Proportional (ESALs)	Variable
Auto	24.88	24.09	4.65	27.74
Pickup	6.17	7.24	1.72	8.92
Other 2 Ax SU	4.73	8.58	7.84	6.28
3 Ax SU	4.40	5.93	8.90	6.08
4 Ax+ SU	0.17	0.15	0.33	1.08
4 Ax– STT	2.63	3.40	5.23	4.16
5 Ax STT	53.26	46.42	63.73	37.49
6 Ax+ STT	0.55	0.56	1.11	1.73
5 Ax– MTT	1.54	1.77	3.02	2.87
6 Ax MTT	0.13	0.14	0.26	0.79
7 Ax+ MTT	0.02	0.01	0.04	0.02
Bus	1.52	1.71	3.19	2.84

Table C.17. Flexible pavement construction cost responsibilities by method for Region 5 farm-to-market roads

	GM	MIA	Proportional (ESALs)	Variable
Auto	60.16	60.16	4.56	54.00
Pickup	30.31	30.31	2.76	30.05
Other 2 Ax SU	4.93	4.93	18.75	5.79
3 Ax SU	0.63	0.63	8.69	1.35
4 Ax+ SU	0.06	0.06	1.87	0.61
4 Ax– STT	1.00	1.00	6.95	1.29
5 Ax STT	2.29	2.29	40.99	4.93
6 Ax+ STT	0.11	0.11	2.70	0.68
5 Ax– MTT	0.02	0.02	0.37	0.04
6 Ax MTT	0.00	0.00	0.00	0.00
7 Ax+ MTT	0.00	0.00	0.00	0.00
Bus	0.49	0.49	12.37	1.25

The following table gives cost responsibilities for load-related rigid pavement rehabilitation and maintenance costs by vehicle type.

Table C.18. Rigid pavement rehabilitation and maintenance cost responsibilities

	Proportional (ESALs)
Auto	0.22
Pickup	0.13
Other 2 Ax SU	2.89
3 Ax SU	4.76
4 Ax+ SU	0.31
4 Ax– STT	2.02
5 Ax STT	83.76
6 Ax+ STT	1.55
5 Ax– MTT	2.37
6 Ax MTT	0.29
7 Ax+ MTT	0.08
Bus	1.63
Total	100.00

The following tables show cost responsibilities for load-related flexible pavement rehabilitation and maintenance costs by each combination of region, highway type, and vehicle class. Phase 1 and Phase 2 results are the same for the generalized method.

Table C.19. Flexible pavement rehabilitation and maintenance cost responsibilities by method for Region 1 interstate highways

	GM	MIA	Proportional (ESALs)	Variable
Auto	1.63	1.63	0.74	4.84
Pickup	0.54	0.54	0.31	1.17
Other 2 Ax SU	3.43	3.43	3.45	3.29
3 Ax SU	4.37	4.37	4.43	4.11
4 Ax+ SU	0.15	0.15	0.15	0.34
4 Ax– STT	2.04	2.04	2.06	2.03
5 Ax STT	81.08	81.08	82.00	77.01
6 Ax+ STT	1.09	1.09	1.10	1.21
5 Ax– MTT	3.46	3.46	3.49	3.54
6 Ax MTT	0.30	0.30	0.30	0.48
7 Ax+ MTT	0.03	0.03	0.03	0.13
Bus	1.89	1.89	1.92	1.86

Table C.20. Flexible pavement rehabilitation and maintenance cost responsibilities by method for Region 1 U.S. and state highways

	GM	MIA	Proportional (ESALs)	Variable
Auto	1.50	1.50	0.72	13.68
Pickup	0.53	0.53	0.30	3.64
Other 2 Ax SU	5.37	5.37	5.39	4.86
3 Ax SU	7.37	7.37	7.45	6.31
4 Ax+ SU	0.51	0.51	0.51	0.78
4 Ax– STT	3.36	3.36	3.39	3.11
5 Ax STT	74.53	74.53	75.31	60.15
6 Ax+ STT	1.36	1.36	1.37	1.61
5 Ax– MTT	2.34	2.34	2.36	2.39
6 Ax MTT	0.09	0.09	0.09	0.50
7 Ax+ MTT	0.02	0.02	0.02	0.13
Bus	3.03	3.03	3.09	2.84

Table C.21. Flexible pavement rehabilitation and maintenance cost responsibilities by method for Region 1 farm-to-market roads

	GM	MIA	Proportional (ESALs)	Variable
Auto	4.28	4.28	1.27	13.33
Pickup	1.69	1.69	0.69	4.30
Other 2 Ax SU	13.74	13.74	14.29	11.96
3 Ax SU	14.72	14.72	15.44	12.78
4 Ax+ SU	0.66	0.66	0.68	1.06
4 Ax– STT	4.39	4.39	4.56	4.68
5 Ax STT	44.60	44.60	46.49	36.01
6 Ax+ STT	1.99	1.99	2.08	2.68
5 Ax– MTT	6.99	6.99	7.16	6.42
6 Ax MTT	0.03	0.03	0.03	0.18
7 Ax+ MTT	0.00	0.00	0.00	0.00
Bus	6.92	6.92	7.29	6.59

Table C.22. Flexible pavement rehabilitation and maintenance cost responsibilities by method for Region 2 interstate highways

	GM	MIA	Proportional (ESALs)	Variable
Auto	0.38	0.38	0.31	2.76
Pickup	0.15	0.15	0.13	0.53
Other 2 Ax SU	2.10	2.10	2.10	2.14
3 Ax SU	3.46	3.46	3.47	3.32
4 Ax+ SU	0.11	0.11	0.11	0.26
4 Ax– STT	3.50	3.50	3.50	3.53
5 Ax STT	80.57	80.57	80.65	77.44
6 Ax+ STT	1.07	1.07	1.07	1.17
5 Ax– MTT	6.19	6.19	6.20	6.11
6 Ax MTT	0.86	0.86	0.86	1.00
7 Ax+ MTT	0.10	0.10	0.10	0.21
Bus	1.50	1.50	1.50	1.54

Table C.23. Flexible pavement rehabilitation and maintenance cost responsibilities by method for Region 2 U.S. and state highways

	GM	MIA	Proportional (ESALs)	Variable
Auto	0.38	0.38	0.38	2.94
Pickup	0.32	0.32	0.32	0.66
Other 2 Ax SU	7.11	7.11	7.11	6.84
3 Ax SU	4.59	4.59	4.59	4.53
4 Ax+ SU	0.59	0.59	0.59	0.65
4 Ax– STT	6.88	6.88	6.88	6.82
5 Ax STT	69.53	69.53	69.53	66.91
6 Ax+ STT	3.78	3.78	3.78	3.90
5 Ax– MTT	1.26	1.26	1.26	1.28
6 Ax MTT	0.21	0.21	0.21	0.36
7 Ax+ MTT	0.33	0.33	0.33	0.38
Bus	5.02	5.02	5.02	4.72

Table C.24. Flexible pavement rehabilitation and maintenance cost responsibilities by method for Region 2 farm-to-market roads

	GM	MIA	Proportional (ESALs)	Variable
Auto	35.88	35.88	8.92	35.88
Pickup	15.12	15.12	6.03	15.12
Other 2 Ax SU	14.35	14.35	24.75	14.35
3 Ax SU	3.50	3.50	7.85	3.50
4 Ax+ SU	0.00	0.00	0.00	0.00
4 Ax– STT	3.16	3.16	5.16	3.16
5 Ax STT	3.74	3.74	5.29	3.74
6 Ax+ STT	0.00	0.00	0.00	0.00
5 Ax– MTT	0.00	0.00	0.00	0.00
6 Ax MTT	8.97	8.97	12.68	8.97
7 Ax+ MTT	0.00	0.00	0.00	0.00
Bus	15.28	15.28	29.31	15.28

Table C.25. Flexible pavement rehabilitation and maintenance cost responsibilities by method for Region 3 interstate highways

	GM	MIA	Proportional (ESALs)	Variable
Auto	0.22	0.22	0.21	0.46
Pickup	0.11	0.11	0.11	0.36
Other 2 Ax SU	2.30	2.30	2.30	2.35
3 Ax SU	1.95	1.95	1.95	1.99
4 Ax+ SU	0.25	0.25	0.25	0.32
4 Ax– STT	1.74	1.74	1.74	1.80
5 Ax STT	87.39	87.39	87.40	86.45
6 Ax+ STT	0.74	0.74	0.74	0.80
5 Ax– MTT	4.21	4.21	4.21	4.23
6 Ax MTT	0.28	0.28	0.28	0.35
7 Ax+ MTT	0.03	0.03	0.03	0.06
Bus	0.79	0.79	0.79	0.85

Table C.26. Flexible pavement rehabilitation and maintenance cost responsibilities by method for Region 3 U.S. and state highways

	GM	MIA	Proportional (ESALs)	Variable
Auto	1.54	1.54	0.61	3.41
Pickup	1.15	1.15	0.50	2.46
Other 2 Ax SU	2.74	2.74	2.70	3.25
3 Ax SU	2.26	2.26	2.32	2.52
4 Ax+ SU	0.34	0.34	0.35	0.60
4 Ax– STT	4.26	4.26	4.34	4.41
5 Ax STT	80.00	80.00	81.33	74.77
6 Ax+ STT	1.36	1.36	1.40	1.62
5 Ax– MTT	4.18	4.18	4.22	4.11
6 Ax MTT	0.61	0.61	0.62	0.92
7 Ax+ MTT	0.01	0.01	0.02	0.13
Bus	1.54	1.54	1.59	1.82

Table C.27. Flexible pavement rehabilitation and maintenance cost responsibilities by method for Region 3 farm-to-market roads

	GM	MIA	Proportional (ESALs)	Variable
Auto	25.27	25.27	0.89	25.27
Pickup	27.32	27.33	1.02	27.33
Other 2 Ax SU	4.66	4.66	2.49	4.66
3 Ax SU	12.87	12.87	21.69	12.87
4 Ax+ SU	0.23	0.23	0.56	0.23
4 Ax– STT	4.71	4.71	7.43	4.71
5 Ax STT	24.19	24.19	63.98	24.19
6 Ax+ STT	0.75	0.75	1.94	0.75
5 Ax– MTT	0.00	0.00	0.00	0.00
6 Ax MTT	0.00	0.00	0.00	0.00
7 Ax+ MTT	0.00	0.00	0.00	0.00
Bus	0.00	0.00	0.00	0.00

Table C.28. Flexible pavement rehabilitation and maintenance cost responsibilities by method for Region 4 interstate highways

	GM	MIA	Proportional (ESALs)	Variable
Auto	1.75	1.75	0.80	2.48
Pickup	0.65	0.65	0.35	0.83
Other 2 Ax SU	3.13	3.14	3.15	3.17
3 Ax SU	5.23	5.24	5.34	5.22
4 Ax+ SU	0.10	0.10	0.10	0.18
4 Ax– STT	2.04	2.05	2.08	2.07
5 Ax STT	81.16	81.12	82.14	79.87
6 Ax+ STT	0.75	0.75	0.76	0.82
5 Ax– MTT	2.85	2.85	2.88	2.87
6 Ax MTT	0.36	0.36	0.37	0.45
7 Ax+ MTT	0.03	0.03	0.04	0.04
Bus	1.93	1.95	2.00	1.98

Table C.29. Flexible pavement rehabilitation and maintenance cost responsibilities by method for Region 4 U.S. and state highways

	GM	MIA	Proportional (ESALs)	Variable
Auto	1.58	1.58	0.70	5.76
Pickup	0.96	0.96	0.50	3.69
Other 2 Ax SU	4.20	4.20	4.22	4.51
3 Ax SU	3.96	3.96	4.04	4.07
4 Ax+ SU	0.49	0.49	0.50	1.06
4 Ax– STT	3.82	3.82	3.90	4.08
5 Ax STT	78.32	78.32	79.37	68.55
6 Ax+ STT	2.01	2.01	2.05	2.40
5 Ax– MTT	1.76	1.76	1.77	2.11
6 Ax MTT	0.28	0.28	0.29	0.83
7 Ax+ MTT	0.01	0.01	0.01	0.01
Bus	2.61	2.61	2.66	2.93

Table C.30. Flexible pavement rehabilitation and maintenance cost responsibilities by method for Region 4 farm-to-market roads

	GM	MIA	Proportional (ESALs)	Variable
Auto	1.06	1.06	0.27	6.39
Pickup	0.60	0.60	0.21	1.42
Other 2 Ax SU	3.34	3.34	3.39	3.64
3 Ax SU	15.78	15.78	15.90	13.31
4 Ax+ SU	0.22	0.22	0.23	0.78
4 Ax– STT	2.76	2.76	2.81	2.94
5 Ax STT	72.86	72.86	73.73	66.75
6 Ax+ STT	1.68	1.68	1.72	2.13
5 Ax– MTT	0.05	0.05	0.05	0.33
6 Ax MTT	0.03	0.03	0.03	0.32
7 Ax+ MTT	0.00	0.00	0.00	0.00
Bus	1.61	1.61	1.66	1.98

Table C.31. Flexible pavement rehabilitation and maintenance cost responsibilities by method for Region 5 interstate highways

	GM	MIA	Proportional (ESALs)	Variable
Auto	1.77	1.77	0.74	2.23
Pickup	0.58	0.58	0.29	0.71
Other 2 Ax SU	2.61	2.61	2.60	2.65
3 Ax SU	3.10	3.10	3.14	3.12
4 Ax+ SU	0.14	0.14	0.14	0.22
4 Ax– STT	2.28	2.28	2.31	2.33
5 Ax STT	82.31	82.31	83.46	81.23
6 Ax+ STT	0.78	0.78	0.79	0.85
5 Ax– MTT	4.68	4.68	4.74	4.71
6 Ax MTT	0.63	0.63	0.63	0.70
7 Ax+ MTT	0.02	0.02	0.02	0.06
Bus	1.12	1.12	1.14	1.19

Table C.32. Flexible pavement rehabilitation and maintenance cost responsibilities by method for Region 5 U.S. and state highways

	GM	MIA	Proportional (ESALs)	Variable
Auto	2.36	2.36	0.99	11.25
Pickup	0.81	0.81	0.42	3.59
Other 2 Ax SU	6.39	6.39	6.50	6.21
3 Ax SU	8.10	8.10	8.29	7.33
4 Ax+ SU	0.29	0.29	0.30	0.79
4 Ax– STT	4.75	4.75	4.85	4.60
5 Ax STT	69.84	69.84	71.03	57.57
6 Ax+ STT	1.02	1.02	1.04	1.51
5 Ax– MTT	3.89	3.89	3.93	3.90
6 Ax MTT	0.32	0.32	0.33	0.74
7 Ax+ MTT	0.01	0.01	0.01	0.01
Bus	2.23	2.23	2.31	2.50

Table C.33. Flexible pavement rehabilitation and maintenance cost responsibilities by method for Region 5 farm-to-market roads

	GM	MIA	Proportional (ESALs)	Variable
Auto	15.43	15.43	2.25	14.89
Pickup	8.02	8.02	1.52	8.74
Other 2 Ax SU	13.83	13.83	17.14	13.62
3 Ax SU	6.13	6.13	8.07	6.08
4 Ax+ SU	1.21	1.21	1.65	1.32
4 Ax– STT	6.57	6.57	7.97	6.57
5 Ax STT	40.01	40.02	49.05	39.87
6 Ax+ STT	1.88	1.88	2.51	2.05
5 Ax– MTT	0.39	0.39	0.48	0.39
6 Ax MTT	0.00	0.00	0.00	0.00
7 Ax+ MTT	0.00	0.00	0.00	0.00
Bus	6.50	6.50	9.38	6.47

APPENDIX D. UPDATES TO THE RENU3 COST MATRIX

Because of the age of the RENU3 program and the changes in materials costs since the program's creation, we thought that it was necessary to update certain parts of the program.

Flexible Pavement Rehabilitation

Here we updated the regional costs for hotmix based on TxDOT bid data. We also replaced the cost function with a computationally less burdensome function that provided statistically satisfactory cost estimations. The cost function is

$$TC = C \times V$$

where TC is the rehabilitation cost per lane-mile, C is the cost in dollars per cubic yard for overlay, and V is the volume in cubic yards of pavement overlay per lane-mile.

Table D.1. Hotmix cost in dollars per cubic yard by region

Region	Cost
1	78.96
2	69.10
3	79.49
4	66.17
5	68.37
Texas Average	71.39

Routine Flexible Pavement Maintenance

Here we updated regional costs for crack-sealing and for surface repair based on TxDOT data.

Table D.2. Crack-sealing cost in dollars per foot and surface repair cost in dollars per cubic yard by region

Region	Crack-sealing	Surface repair
1	0.067	19.81
2	0.075	10.91
3	0.069	17.24
4	0.050	12.53
5	0.069	25.64

Flexible Pavement Seal-coating

Here we updated regional seal-coating costs. We also replaced the cost function with a computationally less burdensome function that provided statistically satisfactory cost estimations. The cost function is

$$TC = C \times TSY$$

where TC is the total cost, C is the cost of seal-coating per square yard, and TSY is the total square yardage to coat.

Table D.3. Flexible pavement seal-coating material cost in dollars per square yard by region

Region	Cost
1	0.48
2	0.49
3	0.72
4	0.53
5	1.10

APPENDIX E. DIVISION OF PAVEMENT CONSTRUCTION COST IN BRIDGE CONSTRUCTION PROJECTS

We estimated the percentages of load-related and non–load-related pavement costs in historical bridge construction projects. In the second column of Table E.1, load-related percentages in common cost components are recommended by experts as shown in Appendix J and these percentages are used to calculate load-related costs in common costs.

In Table E.2, we added up the costs of bid items that we deemed to constitute the load-related portion of bridge construction for each project, and we summed these subtotals across all sample bridge construction projects. We also added together total project costs across all projects and then calculated the percentage of this total that the total load-related costs represented as shown in Table E.3.

Table E.1. Load-related cost breakdown in common cost components by control number

Item number	Load-related % in Common Cost Components	Control Number				
		0907-00-044	1575-03-011	1050-01-014	0815-01-034	1198-03-006
		Costs ($)	Costs ($)	Costs ($)	Costs ($)	Costs ($)
112	100%					
132	20%	660	92,387	163,293	192,518	82,272
134	100%					
150	75%	1,500		8,468		
152	100%					
154	100%					
500	7%	150,000	90,000		118,000	70,000
502	60%	18,000	18,000		16,000	21,000
508	100%	1,692		219,707		
529	30%					
556	100%					
Preliminary & Construction Engineering	40%	73,668	54,420	201,854	113,579	36,304
Load-related Costs in Common Cost Components		**53,716**	**57,346**	**339,458**	**101,795**	**48,476**

(Continued)

Item number	Load-related % in Common Cost Components	Control Number				
		1228-04-011	2635-04-012	0181-01-052	3516-01-005	1068-04-092
		Costs ($)	Costs ($)	Costs ($)	Costs ($)	Costs ($)
112	100%				9,800	
132	20%	9,279	757,297	45,934	70,200	850,854
134	100%					
150	75%			2,210		
152	100%					
154	100%					
500	7%	52,000	485,000			565,000
502	60%	31,500	37,500			172,500
508	100%					
529	30%					
556	100%					
Preliminary & Construction Engineering	40%	57,207	261,904	44,810	110,927	293,053
Load-related Costs in Common Cost Components		**47,278**	**312,671**	**28,768**	**68,211**	**430,442**

Table E.2. Load-related cost breakdown by control number

Item number	Control Number				
	0907-00-044	**1575-03-011**	**1050-01-014**	**0815-01-034**	**1198-03-006**
	Costs ($)	Costs ($)	Costs ($)	Costs ($)	Costs ($)
247	3,308	127,881	546,565	228,725	39,540
251		8,696	58,763		
260		44,415	252,412	132,063	
262			104,664		
276					
305		374	22,386		
310			17,243		
312		5,534		18,174	
314					15,925
316	3,364	26,845	81,134	72,181	4,188
330	17,274				
334					
354					
360	250,635				
3116		3,500	221,290		
3022					
Load-related Costs in Common Costs Components	53,716	57,346	339,458	101,795	48,476
Load-related Costs	328,297	274,590	1,643,915	552,938	68,589
Total Costs	**849,116**	**831,851**	**2,326,628**	**1,309,151**	**418,446**

(Continued)

Item number	Control Number				
	1228-04-011	2635-04-012	0181-01-052	3516-01-005	1068-04-092
	Costs ($)	Costs ($)	Costs ($)	Costs ($)	Costs ($)
247	53,550	259,210	109,920	170,240	64,972
251	13,379				
260	44,958				124,915
262	19,150				
276					33,720
305	389				
310	5,066	18,527	610	22,071	
312					
314					
316	2,878		3,372	51,184	
330					
334				2,516	
354	1,251				8,188
360					665,069
3116			65,021		
3022	140,235	617,700			305,967
Load-related Costs in Common Costs Components	47,278	312,671	28,768	68,211	430,442
Load-related Costs	274,585	948,898	97,772	314,222	1,633,273
Total Costs	**577,268**	**4,003,383**	**516,494**	**1,278,584**	**4,479,524**

Table E.3. Estimated average percentage of load-related pavement costs in bridge projects

Sum of subtotals	6,137,078
Sum of total costs	16,590,444
Average percentage of load-related costs	36.99

APPENDIX F. GENERALIZED METHOD

The mathematical formulation for the GM is shown as follows.

Phase 1 of Generalized Method

Maximize t

Subject to

$$\sum_{i \in N} R_i = C(N),$$ (Completeness Condition)

$$\sum_{i \in S} R_i \le C(S)\text{-}t \quad \text{for all} \quad S \subset N,$$ (Rationality Condition)

R_i, $t \ge 0$ for all $i \in N$,

where N : the set of all vehicle classes.

Phase 2 of Generalized Method

If multiple solutions are found in Phase 1, Phase 2 is implemented.

Minimize $\sum_{i \in N} | r_i - e_i |$ (Minimize the difference between the cost responsibility ratio and the effect ratio)

Subject to

$$\sum_{i \in N} R_i = C(N),$$

$$\sum_{i \in S} R_i \le C(S)\text{-}t^* \quad \text{for all } S \subset N$$

$$r_i = \frac{R_i}{\sum_{i \in N} R_i} \quad \text{for all} \quad i \in N,$$ (Definition of r_i)

$R_i \ge 0$ for all $i \in N$,

where

N : the set of all vehicle classes,

t^*. solution for t as obtained from model defined by Phase 1,

$$e_i = \frac{E_i}{\sum_{i \in N} E_i} \text{ for all } i \in N,$$

E_i : statistical cost effect for vehicle class *i.*

This model can be linearized as follows:

Minimize $\sum_{i \in N} (L_i + H_i)$

Subject to

$$r_i + L_i - H_i = e_i \text{ for all } i \in N,$$

$$\sum_{i \in S} R_i \leq C(S) - t^* \text{ for all } S \subset N,$$

$$\sum_{i \in N} R_i = C(N),$$

$$(\sum_{i \in N} R_i) \times r_i = R_i \text{ for all } i \in N,$$

$$R_i \geq 0 \text{ for all } i \in N,$$

where $L_i = \begin{cases} e_i - r_i \ ; \ r_i < e_i, \\ 0 \ ; \ r_i \geq e_i, \end{cases}$ $H_i = \begin{cases} 0 \ ; \ r_i \leq e_i, \\ r_i - e_i \ ; \ r_i > e_i. \end{cases}$

APPENDIX G. NUMBER OF LANES

As stated in the material on cost allocation, approximate numbers of lanes were calculated based on the guidelines given in the 1997 TRB Highway Capacity Manual. The manual bases its estimates on the amount of passenger car traffic to which the road is subject. The manual classifies all roads as freeways or highways. All interstates were assumed to be freeways, and all others were assumed to be highways (either two-lane or multi-lane).

The following equivalency factors are needed to account for the presence of trucks and buses when measuring traffic with historical ADT values:

Freeway and Multi-lane Highway
1 truck = 1.5 passenger cars

Two-lane Highway
1 truck = 2.2 passenger cars
1 bus = 2 passenger car

The required numbers of lanes were computed based on the Level D traffic service outlined in the manual. This level of service was recommended as an accurate description of average vehicular flow. Service levels vary from Level A (virtually unimpeded vehicle flow, sparse road occupation) to Level F (stop-and-go traffic, heavy vehicle density). Level D service corresponds to a different maximum service flow (MSF) rate for freeways, multi-lane highways and two-lane highways.

Design flow DF and service flow SF for a highway sample are computed as follows:

$$DF = \frac{K \times ADT}{phf}$$

$$SF = MSF \times f_{hv}$$

where K is a factor that converts factor ADT to hourly traffic flow, phf is the peak hour factor, and f_{hv} is a factor to adjust for the effect of heavy vehicles on the traffic stream. If $DF \leq SF$, then a two-lane highway is used for cost calculations. Otherwise, a multi-lane highway is used for cost calculations.

For interstate highways and multi-lane non-interstate highways, we adjust historical traffic volumes as follows to obtain directional design hourly volume (ddhv):

$$ddhv = K \times ADT \times DD$$

where K is the factor mentioned above, DD is the directional distribution factor and ADT is average daily traffic.

The minimum number of lanes required in each direction to handle the adjusted traffic volumes is given by

$$\frac{\text{ddhv}}{\text{phf} \times f_{hv} \times \text{MSF}}$$

where MSF is the appropriate value for interstate or multi-lane non-interstate highways. If the number of lanes is fractional, then it is increased to the next largest whole number.

APPENDIX H. BRIDGE COST ALLOCATION EXAMPLE

The hypothetical example shown in this appendix illustrates how the MIA was used to allocate bridge costs. In this example, a bridge is being built to accommodate three vehicle classes: automobiles (Auto); single-unit, two-axle trucks (SU2); and five-axle, single-trailer trucks (5 Ax STT). Figure I.1 shows the structure of the bridge used to accommodate the vehicles. The strengthening of the deck is required to accommodate the second vehicle class, and the two pillars in the middle are needed for the third vehicle class.

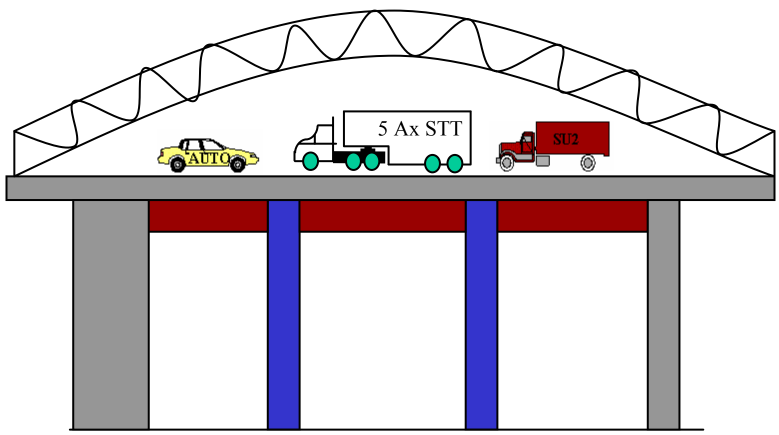


Figure H.1. Bridge and vehicles

Each level of improvement in the bridge has a cost. The basic bridge, which handles up to 10 kips of capacity, has a cost of 100 units. The first level of improvement, which expands capacity to 20 kips, costs 10 additional units (for a total of 110). The second level of improvement, which expands capacity to 30 kips, costs 15 additional units (for a total of 125).

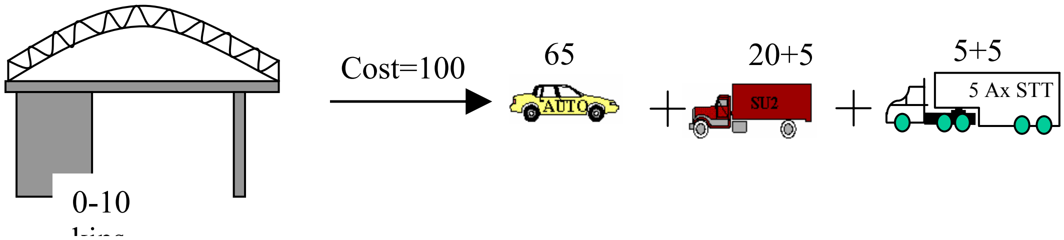
Table H.1 shows the percentage of total VMTs due to vehicles of each class according to weight range.

Table H.1. Percentage of VMTs by vehicle class and weight range

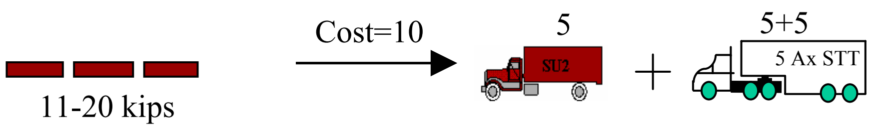
	0–10 kips	11–20 kips	21–30 kips
Auto	65	0	0
SU2	20	5	0
5 Ax STT	0	5	5

The allocation of costs is pictorially represented as indicated below:

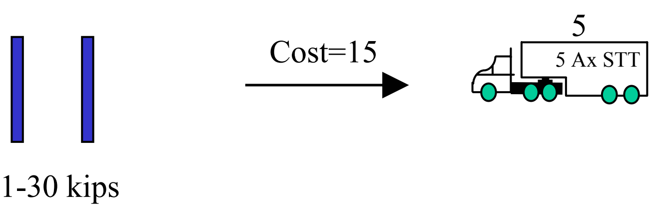
(a) Allocation of the cost of the structure used to support the first vehicle class:



(b) Allocation of additional cost to accommodate the second vehicle class:



(c) Allocation of additional cost to accommodate the third vehicle class:



(d) Cost responsibilities by vehicle class:

Auto : $$100 \times \frac{65}{65+20+5+5+5} = 65.0$$

SU2 : $$100 \times \frac{20+5}{65+20+5+5+5} + (110-100) \times \frac{5}{5+5+5} = 28.3$$

5 Ax STT : $$100 \times \frac{5+5}{65+20+5+5+5} + (110-100) \times \frac{5+5}{5+5+5} + (125-110) \times \frac{5}{5} = 31.7$$

APPENDIX I. NUMBER OF LANES FOR TRAFFIC SAMPLES

For each highway section sample used in the study, we calculated a typical number of lanes required to handle historical traffic volume, using the Highway Capacity Manual (Transportation Research Board 1997). The tables in this appendix show the number of lanes used for each facility.

FLEXIBLE PAVEMENT

Table I.1. Number of lanes in Region 1

IH			US/SH			FM		
2	4	2	1	1	1	1	2	
4	4	2	1	1	2	1	2	
3	3	2	2	1	1	1	2	
6	3	2	2	5	1	1	2	
8	2	2	2	6	1	2	1	
5	3	2	1	3	2	2	1	
5	2	2	2	4	1	2		
7	2	2	1	2	1	2		
6	2	2	1	2	1	1		
3	2	2	1	2	1	1		

Table I.2. Number of lanes in Region 2

IH			US/SH			FM		
2	2	2	1	1	1	1		
2	2	2	1	1	1	1		
4	2	2	1	1	1	1		
4	2	2	1	1	1	1		
4	2	6	1	1	2			
4	2	2	1	1	1			
5	2	2	1	1	2			
2	2	2	1	1	1			
2	2	2	2	1	1			
2	2	2	1	1	1			

Table I.3. Number of lanes in Region 3

IH			US/SH			FM		
2			1	1	1	1		
2			1	2	2	1		
3			1	1	1			
3			1	2	1			
2			1	1	1			
2			1	1	1			
			1	1	1			
			1	1	2			
			1	1	1			
			1	1	1			

Table I.4. Number of lanes in Region 4

IH			US/SH			FM		
2	2	2	2	1	2	1	1	
2	2	2	1	1	2	1	1	
5	2	2	1	4	2	1	1	
2	2	2	1	1	1	1	1	
2	3	2	1	2	2	1	1	
2	2	3	1	1	1	1	1	
4	2	2	1	1	1	2	1	
4	2	2	1	2	1	1	1	
5	2	2	1	1	1	2		
2	2	2	1	1	1	2		

Table I.5. Number of lanes in Region 5

IH			US/SH			FM		
2	2	2	2	2	1	1		
2	2	3	3	2	1	1		
3	2	3	5	2	3	1		
2	2	4	2	1	2	1		
2	2	2	2	3	2	2		
3	2	2	1	5	4	1		
2	2	3	2	2	2	1		
2	3	4	2	2	2	1		
2	3	2	1	2	1	1		
2	4	2	1	1	1	1		

RIGID PAVEMENT

Table I.6. Number of lanes for rigid pavements

Houston			Other Areas				
5	1	1	1	1	1	1	1
5	1	1	1	1	1	1	
3	4	1	1	1	1	1	
4	4	1	1	2	1	2	
3	4		1	1	1	2	
3	4		3	1	1	1	
4	2		1	1	1	1	
4	2		1	1	1	1	
6	3		1	1	1	1	
6	3		1	1	1	1	

APPENDIX J. COMMON COST SURVEY AND RESULTS

TxDOT experts A, B, and C suggested that all 200-, 300-, 2000-, and 3000-level items in its expenditure classification should be counted as wholly load-related. For common cost components, the suggested values for load-related percentages of varied among the experts (Table J.1); our approach was to adopt the minimum suggested value for each component.

Table J.1. Load-related percentages in common cost components

	A	B	C	**Minimum percentage**
Preliminary and construction engineering			40 to 80	**40**
Pavement striping and marking			0 to 40	**0**
Traffic control and protection			60 to 100	**60**
Landscaping			0	**0**
Right-of-way			0	**0**
Grading and drainage			0	**0**
110 Excavation	40	30	0 to 40	**0**
112 Subgrade widening	100	100		**100**
132 Embankment	30	20		**20**
134 Backfilling pavement edges	100	100		**100**
150 Blading	80	75		**75**
152 Road grader work		100		**100**
154 Scraper work		100		**100**
500 Mobilization	7 to 10	10	40 to 80	**7**
508 Constructing detour	100	100		**100**
514 Pavement concrete traffic barrier				
529 Concrete curb, gutter and combined curb and gutter	30 to 50	50		**30**
556 Pipe underdrains	100	100		**100**

APPENDIX K. THE PROPOSED APPROACH FOR THE VARIABLE-NUMBER-OF-LANES SCENARIO

The following definitions are considered for the cost allocation method used for the proposed approach for the variable-number-of-lanes scenario. Let $\boldsymbol{N}$ be the set of natural numbers, n be the number of players in the game, $\boldsymbol{C^n}$ be the set of nondecreasing normalized functions, $q \in \boldsymbol{N^n}$, and $C \in \boldsymbol{C^n}$.

Definition 1. If $\sum_{i=1}^{n} x_i(q;C) = C(N)$, then a method x is called *complete*.

Definition 2. If $x(q;C_1 + C_2) = x(q;C_1) + x(q;C_2)$ for any $C_1 + C_2 \in \boldsymbol{C^n}$, then a method x is called *additive*.

If the cost function can be divided into two distinct and independent cost components, then the allocated costs can be divided into two corresponding components.

Definition 3. If $C(S) - C(S \backslash \{i\}) = 0$ for any $i \in S$, $i \in N$, and $S \in N$, then $x_i(q;C) = 0$. Then, a method x is called *dummy*.

If any player does not contribute to any coalition, then the cost allocated to it is zero.

Definition 4. If $x_i(q,C) \geq x_i((q_1, q_2, ..., q_{i-1}, q_i - 1, q_{i+1}, ..., q_n), C)$, then a method x is called *demand monotonic*.

The cost-share of a player should not decrease when the player increases his demand.

The Aumann-Shapley value (A-S value, 1974) and Shapley value (1953) cost allocations are complete, additive, and dummy. However, the A-S value cannot guarantee the demand monotonicity property for general nondecreasing cost functions.

STEPS FOR PROPOSED PROCEDURE

The proposed approach is composed of the following three steps.

Step 1. Traffic-related pavement cost separation: To separate traffic-related pavement costs into the costs for traffic load and the costs for traffic capacity, the discrete A-S value is used. Suppose that there are m types of players and q_i players of a type i. Further, let $Q = \sum_i q_i$, $T = \sum_i t_i$,

$T' = \sum_i t'_i$, and $t'_i = q_i - t_i$. There are two formulae for the discrete A-S value. The formula by Moulin (1995) is as follows where $i = 1,\ldots, m$:

$$x_i(q;C) = \frac{q_1!\ldots q_m!}{Q} \sum_{t\in[0,q]} \frac{T!}{t_1!\ldots t_m!} \frac{T'!}{t'_1!\ldots t'_m!} \left(\frac{t_i}{T} - \frac{t'_i}{T'}\right) C(t) \,.$$

Another formula by Redekop (2000) is as follows:

$$x_i(q;C) = \sum_{\substack{t\in[0,q] \\ t_i>0}} q_i \times \frac{\binom{q_i-1}{t_i-1}\left(\prod_{j\neq i}\binom{q_j}{t_j}\right)}{T\binom{Q}{T}} [C(t) - C(t_1, t_2, \ldots, t_i - 1, \ldots, t_m)] \,.$$

After separating the cost for traffic, the cost per ESAL and the cost per lane are calculated by averaging because the players in a type are identical. The cost per ESAL (C_e) and the cost per lane (C_l) can be calculated as follows where $i = e$ *or* l:

$$C_i = \frac{x_i(q;C)}{q_i} \,.$$

There are two types of players ESALs and lanes. Further, let q_1 be the total number of players for ESALs, and q_2 be the total number of players for lanes. Then, the cost per lane and the cost per ESAL can be calculated from Redekop's formula as follows:

$$C_l = \frac{q_1!(q_2-1)!}{(q_1+q_2)!} \sum_{t_1=0}^{q_1} \sum_{t_2=1}^{q_2} \frac{(t_1+t_2-1)!}{t_1!(t_2-1)!} \frac{(q_1-t_1+q_2-t_2)!}{(q_1-t_1)!(q_2-t_2)!} \{C(t_1,t_2) - C(t_1,t_2-1)\} \,.$$

$$C_e = \frac{(q_1-1)!q_2!}{(q_1+q_2)!} \sum_{t_2=0}^{q_2} \sum_{t_1=1}^{q_1} \frac{(t_1+t_2-1)!}{(t_1-1)!t_2!} \frac{(q_1-t_1+q_2-t_2)!}{(q_1-t_1)!(q_2-t_2)!} \{C(t_1,t_2) - C(t_1-1,t_2)\} \,.$$

Step 2. Lane assignment: Since the A-S value satisfies the *completeness property*, the sum of costs for traffic capacity and traffic load for the grand coalition equals the total cost for that coalition. The sum of ESALs over all vehicle classes equals the ESALs for the grand coalition (q_1), but the sum of the lanes required for each vehicle class is greater than or equal to the lanes required for the grand coalition (q_2). Hence, to calculate cost responsibilities for each vehicle class, the number of lanes for the grand coalition should be assigned to the vehicle classes. The Shapley value will be used to determine the number of lanes assigned to vehicle class i (L_i). The i[th] Shapley value for n players is as follows where i = 1, …, n:

$$L_i = \sum_{s=1}^{n} \frac{(s-1)!(n-s)!}{n!} \sum_{\substack{S \subseteq N: i \in S \\ |S|=s}} \{F(S) - F(S-i)\} \,.$$

Step 3. Cost allocation: The construction or rehabilitation and maintenance costs are allocated to each vehicle class in proportion to the number of ESALs and the number of lanes.

$$x_i(E_i, L_i) = E_i\, C_e + L_i\, C_l$$

The variables are defined as follows:

$x_i(E_i, L_i)$: Cost allocated to vehicle class i

E_i : ESALs for vehicle class i

C_e: Cost per ESAL

L_i : Number of lanes assigned to vehicle class i

C_l: Cost per lane

AN EXAMPLE

For better understanding of the proposed approach, a simple example is illustrated as follows: Suppose that there are 3 vehicles: two automobiles (A), one pickup truck (P), and one 5-ax-trailer truck (T). 1 base lane, 2 additional lanes, and 4 ESALs are required for all vehicle classes. Traffic loads are 1 ESAL for two automobiles, 1 ESALs for one pickup truck, and 2 ESALs for one 5 axle-trailer truck. Numbers of additional lanes required by each vehicle coalition are in Table K.1.

Table K.1. Number of additional lanes required by each vehicle coalition

Coalition	{A}	{P}	{T}	{A,P}	{A,T}	{P,T}	{A,P,T}
Number of additional lanes	1	1	0	2	2	1	2

Cost function for this example is

$$C(e,l) = l(2 + 3(e)^{0.5})$$

To calculate the A-S value for cost per ESAL (C_e) and cost per lane (C_l), Table K.2 can be used. All the possible including sequences shown in Table K.2 are 6!/2!4! = 15. Suppose that E stands for a unit of ESALs and L for a unit of lanes. A gray-colored column is for the base lane.

Table K.2. All possible including sequences for the A-S value

Sequences	Including Sequences						
1	L	E	E	E	E	L	L
2	L	E	E	E	L	E	L
3	L	E	E	E	L	L	E
4	L	E	E	L	E	E	L
5	L	E	E	L	E	L	E
6	L	E	E	L	L	E	E
7	L	E	L	E	E	E	L
8	L	E	L	E	E	L	E
9	L	E	L	E	L	E	E
10	L	E	L	L	E	E	E
11	L	L	E	E	E	L	E
12	L	L	E	E	E	E	L
13	L	L	E	E	L	E	E
14	L	L	E	L	E	E	E
15	L	L	L	E	E	E	E

A base lane is first included in any possible sequence, and then either E or L is included. The average marginal costs, C_e and C_l, for including E or L in each sequence can be calculated from Table K.2. The A-S values (C_e and C_l) can be also calculated by using the equations shown in Step 1. The calculated values for C_e and C_l are 2.66 and 5.68, respectively.

To calculate number of lanes assigned to each vehicle class by the Shapley value, Table K.3 can be used. All the possible sequences are 3! = 6.

The average marginal number of lanes, L_i, for including A, P, or T in each sequence can be calculated from Table K.3. The Shapley value for L_i can be also calculated by using Equation shown in Step 2. The Shapley values for each vehicle class are:

$L_A = \frac{1}{6}(1+1+1+1+2+1) = 1.67$, $L_P = \frac{1}{6}(1+0+1+1+0+1) = 0.67$, and

$$L_T = \frac{1}{6}(0+1+0+0+0+0) = 0.16 .$$

Table K.3. All possible including sequences for the Shapley value

Sequences	Including sequences			Marginal number of lanes		
1	A	P	T	1	1	0
2	A	T	P	1	1	0
3	P	A	T	1	1	0
4	P	T	A	1	0	1
5	T	A	P	0	2	0
6	T	P	A	0	1	1

In this example, the cost for the base lane (base facility), which has a value of 2, is allocated proportionally by ESALs. Since this cost is non-load-related, however, allocation by VMT would be more appropriate, which is the approach actually taken in this research. Cost responsibilities for each vehicle class are shown in Table K.4.

Table K.4. Cost responsibility calculation for each vehicle class

	Load costs (E_iC_e)	**Capacity costs (L_iC_l)**	**Costs for base lanes (proportional)**	**Cost responsibilities**
Automobile	1×2.66	1.17×5.68	2×0.5	10.30
Pickup truck	1×2.66	0.67×5.68	1×0.5	6.97
5-ax-trailer truck	2×2.66	0.16×5.68	1×0.5	6.73

APPENDIX L. ESALS PER VEHICLE PASS BY PAVEMENT TYPE AND VEHICLE CLASS

L.1 ESALs per Vehicle Pass for Rigid Pavement

ESALs per vehicle pass on rigid pavement are calculated by the following formula:

$$X_i = \frac{\sum_{j=1}^{10} n_{ij} X_{ij}}{\sum_{j=1}^{10} n_{ij}},$$

where n_{ij} is the number of times vehicles of class *i* passed station *j*, X_{ij} is the number of ESALs per vehicle pass by vehicles of class *i* at station *j*, and X_i is the number of ESALs per vehicle pass for class *i*. The result for each class is simply the total number of ESALs produced by the class across all stations divided by the total number of vehicles in that class observed at the stations.

The data used in the calculations of X_i are given in Tables L.1 through L.10.

Table L.1. Station 50230 (50230,50239)

	ESALs per Vehicle Pass	Average Vehicle Weighed	ESALs
Other 2 Ax SU	0.0812	637	51.72
3 Ax SU	0.4497	114	51.27
4 Ax+ SU	3.2488	1	3.25
4 Ax– STT	0.3242	162	52.52
5 Ax STT	1.1163	2,223	2481.54
6 Ax+ STT	1.3699	20	27.40
5 Ax– MTT	0.9171	50	45.86
6 Ax MTT	0.5255	21	11.04
7 Ax+ MTT	8.865	3	26.60
Bus	0.4486	42	18.84

Table L.2. Station 50270 (50270, 50279)

	ESALs per Vehicle Pass	Average Vehicle Weighed	ESALs
Other 2 Ax SU	0.0855	831	71.05
3 Ax SU	1.2302	121	148.85
4 Ax+ SU	3.0391	1	3.04
4 Ax– STT	0.3382	179	60.54
5 Ax STT	1.8474	2,165	3999.62
6 Ax+ STT	1.7901	22	39.38
5 Ax– MTT	1.6254	51	82.90
6 Ax MTT	1.2175	24	29.22
7 Ax+ MTT	2.6421	4	10.57
Bus	0.8062	51	41.12

Table L.3. Station 51210 (51219)

	ESALs per Vehicle Pass	Average Vehicle Weighed	ESALs
Other 2 Ax SU	0.0993	529	52.53
3 Ax SU	0.6434	67	43.11
4 Ax+ SU	0	0	0
4 Ax– STT	0.3064	116	35.54
5 Ax STT	1.4231	1,086	1545.49
6 Ax+ STT	1.7311	7	12.12
5 Ax– MTT	0.493	64	31.55
6 Ax MTT	0.4326	13	5.62
7 Ax+ MTT	5.4731	0	0
Bus	0.5049	21	10.60

Table L.4. Station 51310 (51319)

	ESALs per Vehicle Pass	Average Vehicle Weighed	ESALs
Other 2 Ax SU	0.0629	894	56.23
3 Ax SU	0.4589	134	61.49
4 Ax+ SU	0.1492	0	0
4 Ax– STT	0.2878	251	72.24
5 Ax STT	1.2437	3,301	4105.45
6 Ax+ STT	1.5493	18	27.89
5 Ax– MTT	0.6886	203	139.79
6 Ax MTT	0.3239	59	19.11
7 Ax+ MTT	3.4234	2	6.85
Bus	0.5726	62	35.50

Table L.5. Station 51350 (51359)

	ESALs per Vehicle Pass	Average Vehicle Weighed	ESALs
Other 2 Ax SU	0.2282	1430	326.33
3 Ax SU	0.9779	102	99.75
4 Ax+ SU	0.7120	1	0
4 Ax– STT	0.7193	243	174.79
5 Ax STT	1.9100	3142	6001.22
6 Ax+ STT	2.0127	18	36.23
5 Ax– MTT	1.4908	193	287.72
6 Ax MTT	1.1616	56	65.05
7 Ax+ MTT	1.0003	5	5.00
Bus	0.8828	57	50.32

Table L.6. Station 51620 (51620, 51629)

	ESALs per Vehicle Pass	Average Vehicle Weighed	ESALs
Other 2 Ax SU	0.0469	1100	51.59
3 Ax SU	0.4776	204	97.43
4 Ax+ SU	1.0660	1	1.07
4 Ax– STT	0.3006	106	31.86
5 Ax STT	1.3591	2061	2801.11
6 Ax+ STT	1.1106	12	13.33
5 Ax– MTT	0.7241	70	50.69
6 Ax MTT	0.5468	15	8.20
7 Ax+ MTT	0.7848	1	0.78
Bus	0.6648	52	34.57

Table L.7. Station 51660 (51660, 51669)

	ESALs per Vehicle Pass	Average Vehicle Weighed	ESALs
Other 2 Ax SU	0.0816	1041	84.95
3 Ax SU	0.7404	154	114.02
4 Ax+ SU	0	0	0
4 Ax– STT	0.6239	82	51.16
5 Ax STT	1.9433	2025	3935.18
6 Ax+ STT	1.9833	12	23.80
5 Ax– MTT	2.2061	68	150.01
6 Ax MTT	1.2431	13	16.16
7 Ax+ MTT	4.2716	1	4.27
Bus	0.9747	49	47.76

Table L.8. Station 52210 (52210, 52219)

	ESALs per Vehicle Pass	Average Vehicle Weighed	ESALs
Other 2 Ax SU	0.0568	274	15.56
3 Ax SU	0.4701	45	21.15
4 Ax+ SU	2.6824	0	0
4 Ax– STT	0.2026	58	11.75
5 Ax STT	1.2743	941	1199.12
6 Ax+ STT	1.4747	16	23.60
5 Ax– MTT	0.514	26	13.36
6 Ax MTT	0.4149	8	3.32
7 Ax+ MTT	2.7701	3	8.31
Bus	0.5528	30	16.58

Table L.9. Station 52250 (52250, 52259)

	ESALs per Vehicle Pass	Average Vehicle Weighed	ESALs
Other 2 Ax SU	0.0892	316	28.19
3 Ax SU	0.6178	44	27.18
4 Ax+ SU	2.4353	0	0
4 Ax– STT	0.3829	69	26.42
5 Ax STT	1.7771	917	1629.60
6 Ax+ STT	2.2119	16	35.39
5 Ax– MTT	1.1486	27	31.01
6 Ax MTT	1.1248	11	12.37
7 Ax+ MTT	3.4067	3	10.22
Bus	0.6366	23	14.64

Table L.10. Station 51250 (51259)

	ESALs per Vehicle Pass	Average Vehicle Weighed	ESALs
Other 2 Ax SU	0.0867	633	54.88
3 Ax SU	0.7129	55	39.21
4 Ax+ SU	1.7277	0	0
4 Ax– STT	0.5123	107	54.82
5 Ax STT	1.8274	1,099	2008.31
6 Ax+ STT	2.0047	6	12.03
5 Ax– MTT	1.4937	62	92.61
6 Ax MTT	1.0584	17	17.99
7 Ax+ MTT	8.1701	0	0
Bus	0.5908	25	14.77

Table L.11. Summary

	Total ESALs for Rigid Pavement	Total Number of Vehicles Weighed	Average ESALs per Vehicle pass
Other 2 Ax SU	793.0303	7685	**0.1032**
3 Ax SU	703.4654	1040	**0.6764**
4 Ax+ SU	7.3539	4	**1.8385**
4 Ax– STT	571.6387	1373	**0.4163**
5 Ax STT	29706.63	18960	**1.5668**
6 Ax+ STT	251.1545	147	**1.7085**
5 Ax– MTT	925.5	814	**1.1370**
6 Ax MTT	188.0861	237	**0.7936**
7 Ax+ MTT	72.5985	22	**3.2999**
Bus	284.7068	412	**0.6910**

L.2 ESALs per Vehicle Pass for Flexible Pavement

As stated above, in the flexible pavement designs of the current study, the terminal serviceability index is assumed to be 3.0. Structural numbers of 5.0, 3.5, 2.2 are used for IH, US/SH, and FM, respectively. The following formula is used to calculate ESALs per vehicle pass for flexible pavement:

$$Y_i = \frac{\sum_{j \in J} \sum_{k \in K} n_{ijk} F_{ijk}}{n_i},$$

where J is the set of all weight categories (see the tables below), K is the set of all axle types (single, tandem, or tridem), n_{ijk} is the number of vehicles (at all stations) of class i in weight category j with axles of type k, F_{ijk} is the equivalent single-axle load factor (EALF) for those vehicles, n_i is the number of vehicles in class i (at all stations), and Y_i is the number of ESALs per vehicle pass for class i.

The F_{ijk} must be calculated using the AASHTO formulas, as stated above. First, the following logarithm is computed according to the AASHTO formula:

$$\begin{aligned}\log\left(\frac{W_{tx}}{W_{t18}}\right) &= 4.79\left[\log(18+1) - \log(L_1 + L_2)\right] + 4.33 \cdot \log(L_2) + G_t\left(\frac{1}{\beta_x} - \frac{1}{\beta_{18}}\right) \\ &= 6.125 - 4.79 \cdot \log(L_1 + L_2) + 4.33 \cdot \log(L_2) + G_t\left(\frac{1}{\beta_x} - \frac{1}{\beta_{18}}\right),\end{aligned}$$

where W_{tx} is the number of x-axle loads applied over a span of t years, W_{t18} is the number of 18-kip (80-kN) axle loads applied over t years, L_1 is the load in kips on one single axle, and L_2 is an axle code (1 for single axles, 2 for tandem axles, and 3 for tridem axles). The other symbols are defined as follows:

$$G_t = \log\left(\frac{4.2 - p_t}{4.2 - 1.5}\right),$$
$$\beta_x = 0.40 + \frac{0.081(L_1 + L_2)^{3.23}}{(SN+1)^{5.19} L_2^{3.23}},$$
$$\beta_{18} = 0.40 + \frac{0.081(18+1)^{3.23}}{(5+1)^{5.19}} = 0.5,$$

where SN is the structural number and p_t is the terminal serviceability index.

Computing the right-hand side, we obtain $\log\left(W_{tx} / W_{t18}\right)$ and calculate F_{ijk} according to:

$$F_{ijk} = \frac{W_{t18}}{W_{tx}} = 10^{-\log\left(\frac{W_{tx}}{W_{t18}}\right)}.$$

The axle distribution data in the tables below are used to calculate F_{ijk}. For each interval of vehicle weights, the midpoint of the interval was chosen as the weight for which to calculate the EALF for the interval. In the case of the last weight category, the weight used to calculate the EALF is chosen so that the difference between that weight and the lower bound of the final category is the same as the analogous difference for the previous category. Tables L.12, L.13, and L.14 give axle weight distribution data for 10 stations and an EALF value for each weight category, assuming a structural number equal to 5.

Table L.12. Single axle

Weight Category	Mid-point	EALF (SN=5)	Other 2 Ax SU	3 Ax SU	4 Ax+ SU	4 Ax– STT	5 Ax STT	6 Ax+ STT	5 Ax– MTT	6 Ax MTT	7 Ax+ MTT	Bus
up to 2.2	1.1	**0.00004**	416	0	0	164	42	0	5	1	0	0
2.2 to 4.4	3.3	**0.00121**	7098	18	0	653	358	0	155	67	2	2
4.4 to 6.6	5.5	**0.00867**	2060	51	0	547	391	0	461	143	2	22
6.6 to 8.8	7.7	**0.03421**	987	232	0	759	3342	28	773	228	4	109
8.8 to 11.0	9.9	**0.09669**	556	499	1	548	11894	81	1033	240	13	190
11.0 to 13.2	12.1	**0.21944**	249	172	1	205	3682	28	656	127	7	152
13.2 to 15.4	14.3	**0.42518**	150	41	0	137	279	5	503	76	1	46
15.4 to 17.6	16.5	**0.73061**	102	19	0	98	373	2	300	39	0	5
17.6 to 19.8	18.7	**1.14419**	53	10	0	54	133	0	142	12	0	0
19.8 to 22.0	20.9	**1.66838**	23	1	0	17	17	0	31	2	0	0
22.0 to 24.3	23.2	**2.33662**	12	0	0	5	4	0	3	0	0	0
24.3 to 26.5	25.4	**3.09760**	5	0	0	2	1	0	1	0	0	0
26.5 to 28.7	27.6	**3.99242**	4	0	0	1	2	0	0	0	0	0
28.7 to 30.9	29.8	**5.04446**	3	0	0	1	0	0	0	0	0	0
30.9 to 33.1	32.0	**6.28526**	3	0	0	1	0	0	0	0	0	0
33.1 to 35.3	34.2	**7.75351**	3	0	0	0	1	0	0	0	0	0
35.3 to 37.5	36.4	**9.49421**	3	0	0	0	1	0	0	0	0	0
37.5 to 39.7	38.6	**11.55810**	1	0	0	1	0	0	0	0	0	0
39.7 to 41.9	40.8	**14.00161**	0	0	0	0	0	0	0	0	0	0
41.9 to 44.1	43.0	**16.88673**	0	0	0	0	0	0	0	0	0	0
above 44.1	45.2	**20.28134**	0	0	0	0	0	0	0	0	0	0

Table L.13. Tandem axle

Weight Category	Mid Point	EALF (SN=5)	Other 2 Ax SU	3 Ax SU	4 Ax+ SU	4 Ax– STT	5 Ax STT	6 Ax+ STT	5 Ax– MTT	6 Ax MTT	7 Ax+ MTT	Bus
up to 4.4	2.2	**0.00005**	0	3	0	17	8	0	0	0	0	0
4.4 to 8.8	6.6	**0.00167**	42	225	0	124	1665	3	0	1	3	1
8.8 to 13.2	11.0	**0.01193**	38	273	0	318	6289	14	0	48	7	6
13.2 to 17.6	15.4	**0.04706**	12	109	0	223	5232	29	0	67	8	10
17.6 to 22.0	19.8	**0.13300**	8	80	0	130	4252	36	0	82	5	76
22.0 to 26.5	24.3	**0.30691**	8	100	0	73	3870	28	0	32	3	99
26.5 to 30.9	28.7	**0.59282**	18	114	0	25	5596	32	0	4	4	78
30.9 to 35.3	33.1	**1.01624**	34	88	0	19	8305	19	0	0	3	20
35.3 to 39.7	37.5	**1.58857**	8	30	0	2	1031	10	0	0	2	3
39.7 to 44.1	41.9	**2.31309**	2	15	0	0	71	4	0	0	1	1
44.1 to 48.5	46.3	**3.19229**	0	3	0	0	18	2	0	0	0	0
48.5 to 52.9	50.7	**4.23514**	0	2	0	0	8	0	0	0	1	0
52.9 to 57.3	55.1	**5.46150**	0	0	0	0	5	0	0	0	0	0
57.3 to 61.7	59.5	**6.90327**	0	0	0	0	2	0	0	0	0	0
61.7 to 66.1	63.9	**8.60360**	0	0	0	0	1	0	0	0	0	0
66.1 to 70.5	68.3	**10.61546**	0	0	0	0	1	0	0	0	0	0
70.5 to 75.0	72.8	**13.05965**	0	0	0	0	1	0	0	0	0	0
75.0 to 79.4	77.2	**15.89864**	0	0	0	0	0	0	0	0	0	0
79.4 to 83.8	81.6	**19.25978**	0	0	0	0	0	0	0	0	0	0
83.8 to 88.2	86.0	**23.22839**	0	0	0	0	0	0	0	0	0	0
above 88.2	90.4	**27.89778**	0	0	0	0	0	0	0	0	0	0

Table L.14. Tridem axle

Weight Category	Mid Point	EALF (SN=5)	Other 2 Ax SU	3 Ax SU	4 Ax+ SU	4 Ax– STT	5 Ax STT	6 Ax+ STT	5 Ax– MTT	6 Ax MTT	7 Ax+ MTT	Bus
up to 6.6	3.3	0.00007	0	0	0	0	0	0	0	0	0	0
6.6 to 13.2	9.9	0.00201	0	0	0	0	0	19	0	0	3	0
13.2 to 19.8	16.5	0.01438	0	0	0	0	0	32	0	0	4	0
19.8 to 26.5	23.2	0.05773	0	0	0	0	0	18	0	0	1	0
26.5 to 33.1	29.8	0.16250	0	0	0	0	0	18	0	0	1	0
33.1 to 39.7	36.4	0.36780	0	0	0	0	0	20	0	0	2	0
39.7 to 46.3	43.0	0.71116	0	0	0	0	0	8	0	0	2	0
46.3 to 52.9	49.6	1.22008	0	0	1	0	0	6	0	0	1	0
52.9 to 59.5	56.2	1.90839	0	0	1	0	0	0	0	0	0	0
59.5 to 66.1	62.8	2.78006	0	0	0	0	0	0	0	0	0	0
66.1 to 72.8	69.5	3.85560	0	0	0	0	0	1	0	0	0	0
72.8 to 79.4	76.1	5.11384	0	0	0	0	0	0	0	0	0	0
79.4 to 86.0	82.7	6.59347	0	0	0	0	0	0	0	0	0	0
86.0 to 92.6	89.3	8.33300	0	0	0	0	0	0	0	0	0	0
92.6 to 99.2	95.9	10.38456	0	0	0	0	0	0	0	0	0	0
99.2 to 106	102.5	12.81207	0	0	0	0	0	0	0	0	0	0
106 to 112	109.0	15.64256	0	0	0	0	0	0	0	0	0	0
112 to 119	115.5	18.99013	0	0	0	0	0	0	0	0	0	0
119 to 126	122.5	23.27559	0	0	0	0	0	0	0	0	0	0
126 to 132	129.0	27.99119	0	0	0	0	0	0	0	0	0	0
above 132	135.0	33.06846	0	0	0	0	0	0	0	0	0	0

APPENDIX M. FHWA SOFTWARE FOR STATE HCA

For comparison purposes, the FHWA software for State HCA is executed. Allocation methods used in the software are discussed, and then expenditures and traffic data input are explained. Finally, the cost allocation results are shown.

One may say that wider vehicles need wider travel lanes, and this additional width increases the costs of pavements. However, width is not considered here because current design standards, with 12-foot travel lanes, provide safety, convenience, and a higher level of service with all highway users. Therefore, all highway users should share the width-related costs.

M.1 Cost Allocation Methods

Cost allocation methods depend on cost components because each cost component has its own characteristics. Hence, cost allocation methods will be explained by cost component.

M.1.1 Pavement Construction

If there are no vehicle loadings on any road, at least a certain amount of pavement thickness for that road is required to endure any environmental conditions. This is called a minimum pavement thickness and is not related to vehicle loadings.

According to a guideline for use of the FHWA software, usual values for minimum pavement thickness are between 2.08 and 3.1 for flexible pavement structural number and between 4 and 6 inches for minimum concrete slab thickness. However, the state’s standards for minimum thickness can also be used for these values. After consulting with TxDOT experts, 1.12 for flexible pavement structural number and 5 inches for minimum concrete slab thickness are used for these values. Required pavement thickness and ESALs are calculated by the AASHTO design equations in an iterative way.

Since pavement construction costs for a minimum pavement thickness is not a load-related pavement cost, those costs can be allocated among all vehicle classes proportionally by VMT, PCE-VMT, or a combination of the two. Pavement construction costs for the additional thickness are load-related costs, and can be allocated proportionally by ESALs. This allocation method is often called the minimum pavement thickness method.

M.1.2 Pavement Rehabilitation and Maintenance Costs

There are some differences between the pavement construction costs allocation method and the pavement rehabilitation cost and maintenance cost allocation method.

First, ESALs calculated by the AASHTO procedure are used in the pavement construction cost allocation method, but ESALs calculated by NAPCOM (Nationwide Pavement Cost Model) are used in the pavement rehabilitation and maintenance costs allocation method. Furthermore, costs for a minimum pavement thickness are considered as non-load related costs of the pavement construction costs, and costs for non-load related pavement distresses estimated by NAPCOM are considered as non-load related costs of the pavement rehabilitation costs.

Pavement maintenance costs are allocated proportionally by ESAL miles calculated by NAPCOM. Pavement rehabilitation costs are separated into two: load-related costs and non-load related costs. Non-load-related costs are allocated proportionally by VMT, PCE-VMT, or a combination of the two, and load-related costs are allocated proportionally by ESAL miles calculated by NAPCOM. Load-related pavement rehabilitation cost is usually about 70 to 80 percent of pavement rehabilitation and maintenance cost.

ESALs calculated by the AASHTO procedure have a fourth to fifth-power relationship to axle loads, but ESALs calculated by NAPCOM have approximately a third power relationship.

There are 11 pavement distress types and the separation of load-related costs and non-load related costs are determined by pavement distress type. There are two options to calculate ESAL miles by NAPCOM: option A and option B. ESAL miles calculations for each option are shown in the following. In this research, only option B is used.

Option A: Pavement types, axle types (Single, Tandem, and Triple), and axle weights are considered. However, pavement distress types are not considered.

$$ESAL\ miles = \sum_{aw} \sum_{at} 10^{blef + mlef \times Log_{10}(aw \times at)} \times VMT_{aw,at} \ ,$$

where

blef and *mlef*: regression-approximated parameters that vary among the 12 highway functional classes,

aw: axle weight,

at: axle type.

Option B: Pavement types, axle types (Single, Tandem, and Triple), axle weight, and pavement distress types are considered.

$$ESAL\ \ miles = \sum_{aw}\sum_{at}\sum_{ld} 10^{blef_{ld} + mlef_{ld} \times Log_{10}(aw \times at)} \times VMT_{aw,at},$$

$$= \sum_{aw}\sum_{at}\sum_{ld} 10^{blef_{ld}} (aw \times at)^{mlef_{ld}} \times VMT_{aw,at},$$

where

blef and *mlef*: regression-approximated parameters that vary among the 12 highway functional classes,

aw: axle weight,

at: axle type,

ld: load-related pavement distress types.

M.2 Input Data

All the input data that are used for the FHWA software are shown in this section. Since rural and urban local roads are not in the state-maintained networks, those are excluded in this research. Table M.1 shows the 10 highway functional classes and their abbreviation.

Table M.1. Highway functional class and its abbreviation

Rural	Abbreviation	Urban	Abbreviation
Interstate	Rur Int	Interstate	Urb Int
Other Principal Arterials	Rur OPA	Other Freeways	Urb OFE
Minor Arterials	Rur MA	Other Principal Arterials	Urb OPA
Major Collectors	Rur MajC	Minor Arterials	Urb MA
Minor Collectors	Rur MnC	Collectors	Urb Coll

Expenditures are disaggregated by the existing lane-miles of highway functional classes. The existing lane-miles are calculated by the 1998 road inventory file. Expenditures are shown in Table M.2.

Table M.2. Expenditures by cost component

($ *thousand*)

	New Flexible Pavement	New Rigid Pavement	Flexible Pavement Repair	Rigid Pavement Repair	Flexible Pavement Maintenance	Rigid Pavement Maintenance
Rur Int	9,425	11,088	3,232	83,120	3,735	9,425
Rur OPA	88,212	5,849	30,249	2,006	34,962	2,318
Rur MA	99,722	1,317	34,196	452	39,524	522
Rur MajC	297,570	1,395	102,039	478	117,939	553
Rur MnC	135,521	300	46,471	103	53,712	119
Urb Int	15,291	11,260	5,243	3,861	6,060	4,463
Urb OFE	13,852	10,155	4,750	3,482	5,490	4,025
Urb OPA	49,047	7,659	16,819	2,626	19,439	3,035
Urb MA	21,637	929	7,420	318	8,576	368
Urb Coll	3,044	132	1,044	45	1,206	53

Estimates of VMT by vehicle class and highway functional class were taken from TxDOT data and the FHWA's Highway Statistics (see Appendix N). The estimates are shown in Table M.3.

Table M.3. VMT by highway functional class and vehicle type

(*millions*)

	Rur Int	Rur OPA	Rur MA	Rur MajC	Rur MnC	Urb Int	Urb OFE	Urb OPA	Urb MA	Urb Coll
Auto	8430.7	10364.7	6895.1	8505.6	1535.9	22708.9	15601.4	22626.4	15429.6	7373.6
Pick up & panel	2737.9	4247.2	3287.4	4848.9	831.0	5523.5	3514.4	6007.1	4863.1	3142.2
Other 2Ax SU	66.8	59.5	44.9	70.1	15.4	85.1	39.3	98.8	81.8	31.7
3 Ax SU	640.8	907.2	665.0	935.7	139.4	942.7	606.4	861.7	871.3	506.7
4 Ax+ SU	129.1	180.4	131.1	188.1	27.3	277.4	167.6	210.0	176.9	56.6
4 Ax- STT	3.0	5.4	7.3	11.2	1.3	3.2	4.1	6.2	2.2	5.7
5 Ax STT	185.3	174.9	133.5	172.2	18.0	145.0	84.9	108.1	81.8	74.7
6 Ax+ STT	2789.5	1974.8	932.0	1123.8	77.9	1734.0	639.5	901.8	548.5	106.3
5 Ax- MTT	30.4	39.7	26.7	44.6	3.2	25.2	14.5	24.7	22.1	6.8
6 Ax MTT	138.2	68.5	8.5	36.7	0.5	69.4	22.8	34.0	35.4	4.5
7 Ax+ MTT	31.9	10.8	2.4	1.6	0.0	12.6	2.1	6.2	0.0	1.1
Bus	1.5	1.8	1.2	1.6	0.0	0.0	0.0	0.0	2.2	1.1

Table M.4 is based on the operating gross weight distributions in Tables N.3 and N.6 in Appendix N. Interpolation was used to convert from the weight intervals in Appendix N (which were in 5,000 lbs) to those in Table M.4.

Table M.4. Operating gross weight (OGW) distributions within vehicle classes, percent

Range (kips)	Auto	Pick up & panel	Other 2Ax SU	3 Ax SU	4 Ax+ SU	4 Ax- STT	5 Ax STT	6 Ax+ STT	5 Ax- MTT	6 Ax MTT	7 Ax+ MTT	Bus
0-3	53.49	17.28	0.82	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3-6	37.73	25.30	9.82	0.00	0.00	0.30	0.00	0.00	0.00	0.00	0.00	0.00
6-9	6.23	41.34	27.82	0.00	0.00	0.91	0.00	0.00	0.00	0.00	0.00	0.00
9-12	2.27	14.70	26.02	3.41	0.00	5.27	0.01	0.00	0.00	0.00	0.00	2.50
12-15	0.28	1.37	25.11	5.12	0.00	7.45	0.01	0.00	0.00	0.00	0.00	3.75
15-20	0.00	0.00	6.08	36.24	2.79	14.95	0.74	1.60	1.01	7.48	0.00	14.86
20-25	0.00	0.00	3.02	17.01	10.03	17.06	2.13	1.49	3.30	0.54	0.78	14.16
25-30	0.00	0.00	0.97	10.66	11.23	14.96	4.49	4.08	5.36	2.05	1.80	23.24
30-35	0.00	0.00	0.29	8.86	10.11	14.14	8.44	10.55	5.39	4.77	2.49	23.25
35-40	0.00	0.00	0.05	6.20	8.81	10.73	10.51	10.77	5.32	7.11	4.70	11.90
40-45	0.00	0.00	0.00	4.11	3.18	6.90	6.76	8.92	5.89	8.44	7.64	3.96
45-50	0.00	0.00	0.00	2.88	3.86	3.71	6.23	7.11	7.66	8.72	7.48	1.56
50-55	0.00	0.00	0.00	1.87	4.33	2.16	5.17	5.53	9.27	9.56	6.53	0.81
55-60	0.00	0.00	0.00	1.32	7.72	0.98	4.82	4.94	12.05	10.71	7.96	0.00
60-65	0.00	0.00	0.00	0.87	10.65	0.30	5.84	4.96	11.09	10.29	8.20	0.00
65-70	0.00	0.00	0.00	0.68	8.13	0.10	8.30	5.43	10.93	9.22	8.63	0.00
70-75	0.00	0.00	0.00	0.57	7.08	0.04	9.23	5.79	9.44	7.68	6.98	0.00
75-80	0.00	0.00	0.00	0.20	8.12	0.03	26.42	20.40	13.08	10.64	5.77	0.00
80-85	0.00	0.00	0.00	0.00	2.41	0.00	0.40	0.59	0.00	0.20	0.31	0.00
85-90	0.00	0.00	0.00	0.00	0.79	0.00	0.37	1.95	0.06	0.54	1.20	0.00
90-95	0.00	0.00	0.00	0.00	0.30	0.00	0.03	0.70	0.00	0.63	0.18	0.00
95-100	0.00	0.00	0.00	0.00	0.47	0.00	0.06	1.79	0.00	0.36	0.11	0.00

Table M.4. (Continued)

Range (kips)	Auto	Pick up & panel	Other 2Ax SU	3 Ax SU	4 Ax+ SU	4 Ax- STT	5 Ax STT	6 Ax+ STT	5 Ax- MTT	6 Ax MTT	7 Ax+ MTT	Bus
100-105	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.72	0.01	0.27	7.46	0.00
105-110	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.73	0.15	0.65	12.76	0.00
110-115	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.41	0.00	0.03	0.97	0.00
115-120	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.34	0.00	0.06	1.06	0.00
120-125	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.02	0.94	0.00
125-130	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.05	1.23	0.00
130-135	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.00	0.00	0.04	0.00
135-140	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.77	0.00
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

To calculate ESALs for each pavement section in the FHWA software procedure, system miles and traffic multipliers are used. System miles are used to convert VMT into ADT, and traffic multipliers are used to allow ESALs variations by pavement section. System miles can be calculated by

$$System\ miles(fc) = \frac{Daily\ VMT(fc)}{ADT(fc)},$$

where *fc* is the highway functional class.

Average ADT by highway function class are calculated from the 1998 road inventory file, and VMT was given in Table M.3. Calculated system miles are shown in Table M.5.

Table M.5. System miles by highway functional class

Highway functional class	System miles	Highway functional class	System miles
Rur Int	1,917	**Urb Int**	976
Rur OPA	6,257	**Urb OFE**	1,104
Rur MA	8,062	**Urb OPA**	5,522
Rur MajC	24,361	**Urb MA**	8,569
Rur MnC	11,169	**Urb Coll**	7,443

Average truck VMT of flexible pavement sections by region (5) and highway functional class (10) are calculated from the 1998 road inventory file. Within a highway functional class, traffic multipliers are calculated by the ratio of the average truck VMT of pavement sections by region and highway functional class to the average truck VMT by highway functional class. Table M.6 gives traffic multipliers.

Table M.6. Traffic multipliers

Highway functional class	Region				
	1	2	3	4	5
Rur Int	1.13	0.88	1.33	0.89	1.05
Rur OPA	1.06	0.87	1.10	1.16	0.84
Rur MA	0.96	1.02	0.87	1.05	1.05
Rur MajC	1.03	1.22	0.79	1.09	0.96
Rur MnC	1.00	1.28	0.77	1.15	0.96
Urb Int	1.12	0.77	0.93	0.88	1.07
Urb OFE	1.48	0.31	0.94	1.09	1.02
Urb OPA	1.27	0.84	0.64	0.84	1.07
Urb MA	0.98	1.44	0.73	0.82	1.10
Urb Coll	0.84	1.24	0.62	1.38	1.08

M.3 Results

Running the FHWA software with the above-described data inputs yielded the results in Table M.7.

Table M.7. Percent distribution of Texas highway system costs based on the FHWA software

	Pavement Constructions	Pavement Rehabilitation and Maintenance
Auto	23.25	12.37
Pickup	11.27	6.22
Other 2 Ax SU	7.63	6.60
3 Ax SU	5.31	6.84
4 Ax+ SU	0.84	1.88
4 Ax– STT	2.58	2.28
5 Ax STT	44.37	58.52
6 Ax+ STT	1.27	1.85
5 Ax– MTT	0.95	0.71
6 Ax MTT	0.08	0.06
7 Ax+ MTT	0.04	0.07
Bus	2.42	2.61
Total	100.00	100.00

APPENDIX N: ESTIMATION OF VEHICLE NUMBERS AND VEHICLE MILES OF TRAVEL

MAJOR DATA SOURCES

DATA ON VEHICLE MILES OF TRAVEL

TxDOT supplies annual estimates to the U.S. FHWA for inclusion in the Highway Performance Monitoring System (HPMS). Where necessary, the FHWA adjusts the estimates supplied by states "to improve completeness, consistency, and uniformity" (FHWA 1999, p.V-5). After adjustment, selected estimates are published in *Highway Statistics*.

Highway Statistics provides a breakdown of state VMT among twelve highway functional classes. For rural highways, the classes are interstate, other principal arterial, minor arterial, major collector, and local. For urban highways, they are interstate, other freeways and expressways, other principal arterial, minor arterial, collector, and local. For the higher-order classes, *Highway Statistics* also reports for each state a percentage breakdown of VMT among seven vehicle classes. Because the published statistics omit such breakdowns for the lower-order highway classes, they do not permit calculation of total VMT by state and vehicle class.

Partly for this reason, we turned to the unpublished estimates supplied by TxDOT to the HPMS, which gave the percentage breakdowns for all twelve highway classes. The unpublished estimates had the further advantages of giving a breakdown across all 12 of the vehicle classes used in the HPMS database, rather than the seven broader vehicle classes that are used in *Highway Statistics*. Comparisons between the unpublished estimates and corresponding estimates for Texas in *Highway Statistics* (both for 1998) revealed only slight differences.

The breakdown between passenger cars and light trucks ("pickup trucks") is among the less reliable elements in the HPMS traffic data. The traffic classification devices that are deployed on highways sometimes fail to distinguish properly between these vehicle types, which both have two axles and four wheels. For a more reliable split between passenger car and light truck VMT at the national level, the FHWA combined the HPMS data with data from other sources that are discussed below (see FHWA 1996). The present study's attempt to apply this approach to Texas data did not produce valid results. Consequently, we have used the HPMS estimates of Texas VMT without adjustment.

DATA ON VEHICLE REGISTRATIONS

The Vehicle Titles and Registration Division of TxDOT (VTR) maintains an extensive database on Texas-based vehicles. For this study, VTR supplied us with special tabulations from this database for the calendar year 1999. For the larger registration classes, we obtained breakdowns of nonexempt vehicles by registered weight and, in the case of passenger cars, by vehicle age. For nonexempt buses, we also had a breakdown among transit, private, and motor buses (see below). The assumption in our calculations was that the percentage breakdowns were unchanged between 1999 and the base year for our analysis, 1998.

Our analysis also makes some use of the 1998 registration data for Texas that are reported in *Highway Statistics*. The FHWA based these data on an annual report submitted by TxDOT's Finance Division, which, in turn, relies on an annual report prepared by the department's VTR

Division. Both the FHWA and the Finance Division modify the data they receive. The changes most relevant to the present discussion pertain to government-owned vehicles, vehicles that are transferred out-of-state, and the split between passenger cars and light trucks.

Government-owned vehicles

The VTR report shows the number of vehicles (including trailers) in each of the forty-four Texas registration classes. The Finance Division uses this report to complete a form that states submit to the FHWA, a form that covers the annual number of registrations by vehicle category (Form-561). The categories in this form are fewer than, and in other respects different from, the registration classes in the VTR report. The Finance Division thus has to map the VTR classes into the FHWA categories.

The FHWA category that comprises state and local government vehicles corresponds closely with "exempt" vehicles in the VTR report. Texas exempts from registration fees all government vehicles, which are overwhelmingly owned by state and local rather than the federal government (see *Highway Statistics 1998*, Table MV-7). The Finance Division has concerns about the reliability of the count of exempt vehicles in the VTR report, however, so it conducts its own count of state and local government vehicles for the FHWA.

Vehicles transferred out-of-state

To complete the FHWA form, each state must report the number of vehicles that transfer out-of-state during the year and deduct this from the number of vehicle registrations. The purpose of this deduction is to avoid double counting vehicles that register in more than one state, so that the estimates add up across states to the national total. The Finance Division of TxDOT obtains a figure on the number of vehicles transferred out of Texas during the year, but lacks a breakdown of this figure by vehicle category. In the absence of a breakdown, Finance classifies all the transferred vehicles as "passenger cars," which the vast majority of them probably are.

Distinguishing passenger cars from light trucks

The FHWA adjusts the state-supplied data on vehicle registrations to correct mistakes and omissions and to maintain consistency across states; the adjusted data are then published in *Highway Statistics*. A general problem is the absence of a clear distinction in the state registration records between passenger cars and light trucks. In Texas, owners of sport utility vehicles, some vans and minivans can register their vehicles as either passenger cars or "commercial vehicles" with truck plates. Such vehicles are nevertheless light trucks ("pickups") in the FHWA classification of vehicles, which our study attempts to follow. To reclassify the light trucks that are registered as passenger cars, FHWA has developed a model to adjust the state-supplied data on registrations. We have not ascertained the details of the model, which is reported to be complicated.

DATA ON VEHICLE OPERATING WEIGHTS

Texas weigh-in-motion data

Weigh-in-motion (WIM) is a technology for weighing vehicles as they move at normal speed over a scale embedded in the road. A WIM scale measures the weights of individual axles and the total gross weight of the vehicle (the sum of all the axle weights). Governments use WIM data for highway planning and weight enforcement purposes.

The present study uses 1998 data on gross vehicle weight by vehicle class, collected at eighteen WIM stations on Texas interstate highways. Separate distributions of gross vehicle weight were available for eight of this study's vehicle classes. Data were unavailable for passenger cars, pickup trucks, and for two uncommon vehicle classes: single-unit trucks with four or more axles and multi-trailer trucks with seven or more axles.

The Highway Revenue Forecasting Model (HRFM)

For the vehicle classes for which Texas WIM data were unavailable, we took data on operating weight from the Highway Revenue Forecasting Model version 5 (HRFM-5). A national-level model developed at the FHWA, the HRFM contains operating weight distributions by vehicle class in 5,000 lb intervals (see FHWA 1998a). The distributions emerged from analysis of more than 12 million WIM observations from around the nation. Of these observations, about 6.7 percent were rejected because the recorded weights were implausible for the class of vehicle to which the observation related. Implausible recorded weights could stem from misclassification of vehicle types or from errors in the weight measurements. In many vehicle classes, the rejection rate was negligible. However, for one of the vehicle classes for which we relied on the HRFM, single-unit trucks with 4 or more axles, the rejection rate was 47 percent.

The HRFM also contains for each class a distribution of vehicles by registered weight (again in 5,000 lb intervals) and a joint distribution of vehicles by registered and operating weight. The registered weight distributions were derived from the 1992 Truck Inventory and Use Survey and other data sources; the joint distribution, from special weight studies conducted in several western states, with most of the data coming from Oregon.

VEHICLE INVENTORY AND USE SURVEY

The U.S. Census Bureau has been conducting a national survey of privately owned trucks every five years. Previously known as the Truck Inventory and Use Survey, it is now known as the Vehicle Inventory and Use Survey in anticipation of it eventually including vehicles other than trucks. The survey results tend to be less reliable for an individual state than for the nation because of differences in sample size. Our analysis relies on 1997 VIUS data on the number of light ("pickup") trucks in Texas, on the national distribution of farm trucks among vehicle classes, and on average annual mileage by vehicle class. We used Texas-specific estimates when we judged the sampling errors in these estimates to be sufficiently small. Otherwise, we used national estimates as proxies for the Texas values.

Annual mileage per vehicle

Estimates of average annual mileage per truck were Texas-specific only for the single-unit classes with fewer than three axles. For single-unit trucks with more than three axles and for all but one of the combination classes, we judged that the Texas sample contained too few observations to yield statistically reliable estimates. The exception was the most numerous combination class, five-axle combinations with a single trailer. For this class, the estimate was virtually the same for Texas as for the nation, somewhat over 70,000 annual miles per vehicle. The choice between these estimates was therefore inconsequential; we chose the national estimate simply to be consistent with our use of national estimates for all the other combination classes (along with single-unit trucks with more than three axles).

Some HCA databases differentiate mileage per truck by both vehicle class and registered weight. In the database for the previous Texas HCA, the mileage per truck within a vehicle class increased with registered weight. For example, among single-unit trucks with three or more axles, annual mileage per vehicle increased from about 11,000 at less than 26,000 lbs to about 20,000 at more than 50,000 lbs (national-level estimates for 1990). The direct source for these estimates was a precursor to the current HRFM; the original source was probably the Truck Inventory and Use Survey.

The current HRFM, in contrast, does not differentiate mileage per truck within a vehicle class. According to an FHWA source, this owes to concerns about the adequacy of sample sizes in the 1992 Truck Inventory and Use Survey. Only for the more numerous vehicle classes were the samples considered adequate for a breakdown by registered weight; rather than include the breakdown for these classes alone, the modelers decided to omit it entirely.

The state HCA software recently developed for the FHWA contains a default database with estimates of annual mileage per truck by registered weight. The estimates differ among states and between single-unit and combination trucks. The estimates, which are based on the 1997 VIUS, vary positively with registered weight.

ESTIMATION: PASSENGER CARS

For passenger cars, we took the number of Texas-registered vehicles from *Highway Statistics, 1998*. The percentage distribution by registered weight came from the VTR database and showed less than one percent of vehicles as having weights greater than 6,000 lbs. For these vehicles that exceed this threshold, the registration fee in Texas increases with registered weight. For other passenger cars, the fee varies among vehicle age groups: three years or less ($58.80), between three and six years ($50.80), or more than six years ($40.80). From the VTR database, we obtained the percentage distribution among these age categories, among passenger cars registered at under 6,000 lbs.

Revenues from fuel taxes depend on fuel consumption, which, in turn, depends on vehicle operating weight. To convert the registered weight distribution for Texas passenger cars to an operating weight distribution, we used the distribution of operating and registered weight from the HRFM. For registered weights under 5,000 lbs, the HRFM indicates that, nationally, 8.3 percent of passenger cars on the road have operating weights in the next highest interval, 5,000 to 10,000 lbs. The HRFM records no passenger cars registered at over 5,000 lbs, whereas our database shows 2.9 percent of Texas vehicles as being in the 5,000 to 10,000 lb interval.[16] For these vehicles, we assume operating weights to be within the same interval as registered weight. So our estimate is that about 10.9 percent of Texas passenger cars on the road operate at a weight between 5,000 and 10,000 lbs ($10.9 \approx 2.9 + 97.1 * 8.3$). The other 90.1 percent of Texas passenger cars operate at less than 5,000 lbs according to our estimates.

[16] Actually, the Texas data showed that 0.47 percent of passenger cars are registered at over 10,000 lbs. However, since we have no information on the fuel economy of vehicles operating at these weights, we have reallocated these vehicles to the 5,000 to 10,000 lb interval. Of the Texas "passenger cars" with registered weights in this interval, some may be light trucks rather than passenger cars according to the FHWA vehicle classification. (Recall that owners of sport utility vehicles and some vans and minivans can register their vehicles as passenger cars.) This might explain why the HRFM database, which was developed at the FHWA, records no passenger cars with registered weights over 5,000 lbs, whereas the TxDOT registration files shows a small number in this range (2.9 percent).

ESTIMATION: BUSES

From the VTR database, we ascertained the numbers of buses paying Texas registration fees in 1998. The largest category, with 9,445 registrations, was "private" buses, which are not operated for compensation. Transit buses formed the smallest category, with fewer than 300 registrations recorded. The vast majority of transit buses are exempt from registration fees on account of local government ownership: in 1998, there were 5,151 such buses according to *Texas Transit Statistics* (TxDOT, various editions). Motor buses are a registration category that covers nonexempt buses other than transit and private buses.

For private buses and transit buses, we estimated VMT in Texas by multiplying estimated annual mileage per bus with the number of buses registered in Texas. Data reported by the American Public Transit Association indicate that annual mileage per transit bus was 30,700 in 1998 (see http://www.apta.com/stats/). For private buses, we found no data on mileage and used our own conjecture of 17,000 miles per vehicle-year.

Motor buses called for a different approach to estimating annual VMT in Texas because, unlike the other bus classes, they engage in substantial interstate travel. Motor buses registered in Texas may incur a significant portion of their mileage out-of-state; likewise, vehicles registered in other states may account for a significant share of the motor bus mileage in Texas.

For motor buses, our approach to estimation relied partly on a study of the motorcoach industry in the United States and Canada (R.L. Banks, Inc. 2000). The industry consists of commercial motor carriers and a motorcoach is:

"a vehicle designed for long distance transportation of passengers, characterized by integral construction with an elevated passenger deck located over a baggage compartment. It's at least 35 feet in length and carries more than 30 passengers."

Under this definition, the vehicles considered in the study would seem to largely coincide with the category "motor buses" in our study. Exceptions to this characterization include the motor coaches that provide express services between Dallas suburbs and downtown; these are transit buses in our classification since they operate within a metropolitan area. The exceptions are rare enough, however, that the study's stated objective was to profile the "intercity bus industry". Based on the results of its survey, the study estimated that scheduled services accounted for nearly half (49.9) of the motorcoach industry's annual mileage. Charter bus services accounted for another third of the annual mileage, while smaller industry segments included tour buses (6.7), commuter buses (5.3), and airport shuttles (1.6).

Generalizing from this, we assume that scheduled services account for nearly half (49.9) of annual motor bus VMT in Texas. In addition, for the scheduled motor bus services in Texas, we set 1998 VMT at 39,261,000 miles; this is the Texas Comptroller's estimate of VMT that would have qualified in 1998 for the diesel fuel tax concession for scheduled intercity bus services (see the discussion of that concession in section 2.1 of this report.) Combining this estimate with the assumption that scheduled services account for 49.8 percent of all motor bus (intercity) services, we estimate that total motor bus VMT in Texas was 78,680,000 in 1998 (=39,261,000/49.9).

As Chapter 2 explained, we collected no data on school buses because they are almost entirely exempt from taxes on road users.

ESTIMATION: TRUCKS

Our final estimates of the number of Texas trucks in 1998 appear in four matrices. Each matrix cross-tabulates the number of trucks by vehicle class and weight. One pair of matrices relates to single-unit trucks and the other to combinations. Within each pair, one matrix relates to registered weight and the other to operating weight. The construction of the matrices involved a complicated series of steps to combine the best available data from several sources.

SINGLE-UNIT TRUCKS

Estimating the distribution of trucks by vehicle class

For each of the heavy single-unit truck classes, we measured the number of Texas trucks in vehicle-equivalents to allow for interstate travel (see section 1.2). The number of vehicle equivalents, it will be recalled, is the ratio of Texas VMT to average annual mileage per vehicle. The sources of the estimates of numerator and denominator have already been described in this appendix: the estimates of Texas VMT by vehicle class came from the HPMS, and the estimates of average annual mileage per vehicle came from the 1997 VIUS.

For light trucks, interstate travel is less prevalent, so rather than resorting to the vehicle-equivalent measure, we have simply estimated the number of Texas-registered vehicles in this category. Our starting point was the VIUS-based estimate of the number of private light trucks registered in Texas in 1997. This estimate is more reliable than the *Highway Statistics* estimates of the number of light truck registrations in Texas.[17] However, we had to rely on the *Highway Statistics* estimates to update the VIUS estimate from 1997 to 1998. (We applied the percentage growth rate in the *Highway Statistics* estimate between these years.) After the update, we wound up with a 1998 estimate of the number of privately owned light trucks registered in Texas. To estimate the number of publicly owned light trucks in Texas, we ascertained the total number of publicly-owned trucks in Texas from *Highway Statistics 1998*; we then multiplied this total by an estimate of the proportion of publicly owned trucks in Texas that are light trucks (an estimate taken from the 1992 database for the last Texas HCA study).

The predominance of light ("pickup") trucks among trucks on Texas roads shows up in our estimates for 1998. Of approximately 5 million single-unit trucks, light trucks accounted for an estimated 87.7 percent (Table N.1).

[17] For one thing, the *Highway Statistics* criterion for classifying a truck as "light" (gross vehicle weight under 10,000 lbs) differs somewhat from that employed in this report (two wheels and four axles). We can extract an estimate consistent with our definition from the VIUS data but not from *Highway Statistics*.
For another thing, recall that the primary data source for the *Highway Statistics* estimate is a TxDOT report that tallies registrations by vehicle class. Light trucks cannot be neatly equated with some subset of these classes: for example, as we already noted, some sport utility vehicles are registered as passenger cars, yet they count for our purposes as light trucks. Despite some adjustments to the TxDOT figures, such classification problems remain in the vehicle numbers published in *Highway Statistics*. The VIUS, on the other hand, collects enough information on surveyed vehicles to make such misclassification much less likely.

Table N.1. Percent distribution of single-unit trucks by vehicle class, Texas 1998

Pickups	Other 2 Ax SU	3 Ax SU	4 Ax+ SU
87.67	10.66	1.63	0.04

Estimating the percent distribution of trucks by registered weight

For the percent distribution of single-unit trucks by registered weight, we have used as a proxy the corresponding distribution within the Texas registration class "commercial vehicle." This class consists of vehicles, excluding motorcycles, that are "designed or used primarily to transport property." The vast majority of vehicles in this class are single-unit trucks. Few "commercial vehicles" are combinations: the vast majority of combinations involve truck-tractors, which register in a separate "combination" class.[18]

Of somewhat greater significance is that some single-unit trucks are registered in categories other than "commercial vehicle." Such vehicles include single-unit farm trucks and the sport utility vehicles and similar trucks that register as passenger cars. (Sport utility and similar vehicles can be registered as passenger cars or as commercial vehicles with truck plates at the option of the registrant.[19]) Since we were unable to obtain tabulations of registration data for these vehicles separately, we had to make do with the "commercial vehicle" data as a proxy for registered weight distribution among single-unit trucks.

The registered weight distribution that we obtained for commercial vehicles contained thousand pound intervals up to 80,000 lbs, with the top interval being "over 80,000" lbs. The distribution is aggregated to broader weight intervals in Table N.2, in the column headed "All SU Trucks TxDOT." The entries in the other columns of Table N.2 were derived in the manner explained below.

[18] Some straight trucks (not truck-tractors) normally operate in combination with a full trailer. These vehicles cannot register as combinations, and would be mainly in the "commercial" or "farm" registration classes. However, according to published VIUS estimates for 1997, there were only 2,300 such vehicles in Texas. Conceivably, the commercial truck registrations also include a small number of exceptionally lightweight truck-tractors. To register in the combination class, a truck-tractor must have a manufacturer's rated carrying capacity of more than one ton and be used in combination with a semitrailer that has a gross weight of more than 6,000 lbs.

[19] The "commercial" in "commercial truck" designates a vehicle that is designed or used primarily to transport property. Sport utility vehicles, vans, and minivans may fall in that category even if used for nonbusiness purposes. Whether it is cheaper to register such a vehicle as a commercial truck or a passenger car depends on the vehicle's age and weight.

Table N.2. Percent distribution of single-unit trucks by registered weight: all vehicles and within each class, Texas 1998

	Pickups	Other 2 Ax SU	3 Ax SU	4 Ax+ SU	All SU trucks TxDOT
weight (000s lbs)					
under 5	54.33	13.2	0.0	0.0	49.04
5–10	44.95	72.41	0.0	0.0	47.13
10–15	0.72	4.41	0.0	0.0	1.10
15–20	0.0	3.81	6.69	0.0	0.52
20–25	0.0	2.41	11.91	0.0	0.45
25–30	0.0	2.79	22.75	0.0	0.67
30–35	0.0	0.89	10.55	0.33	0.27
35–40	0.0	0.05	3.88	0.14	0.07
40–45	0.0	0.0	5.56	0.0	0.09
45–50	0.0	0.0	17.71	0.31	0.29
50–55	0.0	0.0	10.99	1.22	0.18
55–60	0.0	0.0	1.84	1.1	0.03
60–65	0.0	0.0	4.77	5.59	0.08
65–70	0.0	0.0	3.09	60.7	0.07
70–75	0.0	0.0	0.08	7.23	…
over 75	0.0	0.0	0.19	23.37	0.01
NOTE: Column entries may not add up exactly to 100 because of rounding.					

… less than 0.01 percent

Estimating the percent distribution of trucks by registered weight and vehicle class

The preceding discussion explained how we formed two percentage distributions for single-unit trucks. One distribution gives a breakdown by registered weight; the other, by vehicle class. In the following discussion, these are the "marginal distributions."

The next task was to create a matrix giving the joint percentage distribution by both registered weight and vehicle class. To do this, we created a preliminary matrix based on data from the HRFM and from 1998 Texas WIM observations. Next, we adjusted the preliminary matrix to force the row and column totals to agree with both marginal distributions. These steps are described below.

Creating the preliminary matrix

To create the preliminary matrix, we needed a percent distribution of vehicles within each class by registered weight. The data sources for this distribution differed among vehicle classes, depending on the availability of Texas WIM data.

The WIM data were unavailable for light trucks (two-axle, four-tire) and for single-unit trucks with four or more axles. For these classes, we imported the percent distribution by registered weight from the HRFM (national-level data).

For the other two single-unit classes—vehicles with two axles and six tires and vehicles with three axles—we took the operating weight distributions from the WIM data. The distributions start with the interval, under 7,000 lbs, followed by intervals in either 4,000 or 5,000 lb increments. To convert these operating weight distributions to registered weight distributions, we relied on the HRFM. The HRFM includes a matrix for each class with the joint distribution of vehicles by registered and operating weight (see above). To use this matrix, we had to alter the weight intervals in the WIM distributions to match those employed in the HRFM (0–5,000, 5000–10,000 and so on). The alteration to the original WIM intervals was through linear interpolation, except in the first interval, 0–7,000 lbs. Over that interval, linear interpolation would be too unrealistic: of the trucks operating at under 7,000 lbs, fewer than one-seventh, if any, would weigh less than 1,000 lbs For the two-axle six-tire class, the WIM distribution showed some trucks at under 7,000 lbs, and we devised a special procedure to deal with this interval.[20]

The final step in creating the preliminary matrix was to combine the within-class distributions by registered weight with the marginal distribution by vehicle class. For illustration, consider the class of single-unit trucks with two axles and six tires. The within-class distribution indicated that 43.4 percent of these trucks weighed between 5,000 and 10,000 lbs, while the marginal distribution showed that this class accounted for 10.7 percent of single-unit trucks. Multiplying these percentages gives the preliminary estimate that 4.6 percent of all single-unit trucks are in this class *and* weigh between 5,000 and 10,000 lbs.

Adjusting the preliminary matrix

The preliminary matrix, by construction, was consistent with the marginal distribution by vehicle class in Table N.1. However, it could not also agree with the marginal distribution by registered weight (the far-right column of Table N.2), given the differences in the underlying data sources. To obtain a matrix that agrees with both marginal distributions, we adjusted the preliminary matrix using an iterative proportional fitting technique. Willumsen and Ortuzar (1994) describe this technique—which they attribute to Furness (1965)—and its application to trip distribution modeling.

Table N.2 shows the matrix that emerged from the iterative proportional fitting. For more accurate revenue allocation, we expanded this matrix to break down the weights into one thousand pound intervals. Within each of the intervals in Table N.2, we applied the percent

[20] The procedure was to: (i) linearly interpolate over the interval 7,000–11,000 lbs to estimate the percent of trucks with operating weights between 7,000 and 10,000 lbs (ii) combine the new interval with the interval 0–7,000 lbs to get the percent of trucks with operating weight under 10,000 lbs; (iii) divide the trucks with operating weight under 10,000 lbs between the intervals, 0–5,000 lbs and 5,000–10,000 lbs in the same proportion as in the HRFM database.

distribution of registered weight in thousand pound intervals among all single-unit trucks, based on the VTR registration files.

Estimating the percent distribution of trucks by operating weight and vehicle class

Our estimated distribution of single-unit trucks by vehicle class and operating weight (Table N.3) is derived from Table N.2 and the HRFM database. Table N.2 contains a distribution of single-unit trucks by vehicle class and registered weight. To convert from registered weight to operating weight, we used the aforementioned joint distribution in the HRFM.

Table N.3. Percent distribution of single-unit trucks by operating weight and vehicle class, Texas 1998

	Pickups	Other 2 Ax SU	3 Ax SU	4 Ax+ SU
weight (000s lbs)				
under 5	28.81	1.36	0.00	0.00
5–10	68.90	46.37	0.00	0.00
10–15	2.29	41.86	8.53	0.00
15–20	0.00	6.08	36.24	2.79
20–25	0.00	3.02	17.01	10.03
25–30	0.00	0.97	10.66	11.23
30–35	0.00	0.29	8.86	10.11
35–40	0.00	0.05	6.20	8.81
40–45	0.00	0.00	4.11	3.18
45–50	0.00	0.00	2.88	3.86
50–55	0.00	0.00	1.87	4.33
55–60	0.00	0.00	1.32	7.72
60–65	0.00	0.00	0.87	10.65
65–70	0.00	0.00	0.68	8.13
70–75	0.00	0.00	0.57	7.08
75–80	0.00	0.00	0.20	8.12
80–85	0.00	0.00	0.00	2.41
85–90	0.00	0.00	0.00	0.79
90–95	0.00	0.00	0.00	0.30
95–100	0.00	0.00	0.00	0.47
NOTE: Column entries may not add up exactly to 100 because of rounding				

COMBINATION TRUCKS

We used basically the same procedures for combination trucks as for single-unit trucks. The end result was two matrices giving a distribution of vehicles by class and by either registered weight or operating weight. The marginal distribution by vehicle class (Table N.4) was based on vehicle-equivalents for each class.

Table N.4. Percent distribution of combination trucks by vehicle class, Texas 1998

4 Ax-STT	5 Ax STT	6 Ax+ STT	5 Ax-MTT	6 Ax MTT	7 Ax+ MTT
18.20	76.86	2.02	2.49	0.38	0.06

The marginal distribution by registered weight (far-right column of Table N.5) was based on the distribution of registered weight within the Texas registration class, "combination trucks," which consists of truck-tractors. Combinations involving straight trucks (rather than truck-tractors) would be missing from this distribution, as might be some exceptionally light truck-tractors; however, these omissions are minor. Also missing from this distribution are truck-tractors registered as "apportioned," which are nearly as numerous as vehicles registered in the "combination class" (in 1998, these numbered about 58,000 and 65,000, respectively). Apportioned vehicles presented a data problem for our analysis because they include a large number of vehicles, mainly trailers, in addition to truck-tractors (see section 1.2). Relatively late for this report, we received from TxDOT a tabulation of registered weight among apportioned vehicles excluding trailers. Fortunately for us, the percent distribution was very similar to that for the registration class "combination trucks."

Table N.5 shows the estimated distribution of combination trucks by vehicle class and registered weight, using broad weight intervals. To break this distribution into thousand pound intervals, and to derive from it a distribution by vehicle class and operating weight (Table N.6), we used the same procedures as we employed for single-unit trucks, with one difference. The difference occurred in the use of the national data from the HRFM to convert registered weights to operating weights. Some states place a legal limit on gross vehicle weight that exceeds the 80,000 lbs allowed on Texas roads. For this reason, trucks of a given registered weight will tend to operate at somewhat heavier weights in states other than Texas. To allow for this, we modified the (national-based) HRFM distribution for operating weights exceeding 75,000 lbs, to better reflect the Texas situation. Specifically, among vehicles exceeding this weight, we imposed the percentage weight distribution found in the Texas WIM data. Only the distributions for combination trucks were modified because very few single-unit trucks exceed 75,000 lbs in the HRFM operating weight distributions.

Table N.5. Percent distribution of combination trucks by registered weight: all vehicles and within each class, Texas 1998

	4 Ax-STT	5 Ax STT	6 Ax+ STT	5 Ax-MTT	6 Ax MTT	7 Ax+ MTT	All Combination Trucks, TxDOT
weight (000s lbs)							
Under 20	3.52	0.00	0.00	0.00	0.00	0.00	0.59
20–30	22.87	0.85	0.00	0.00	0.00	0.00	3.95
30–40	31.97	0.95	0.00	0.00	0.00	0.00	5.49
40–50	26.83	7.86	2.82	0.00	0.00	0.00	6.25
50–60	12.14	13.41	7.81	8.71	0.00	0.00	7.01
60–70	1.20	3.06	3.90	6.91	11.63	22.18	8.15
70–80	1.48	73.87	85.45	84.38	88.36	77.63	68.53
Over 80	…	…	0.02	…	0.01	0.19	0.04

NOTE: Column totals may not add exactly to 100 because of rounding

… less than 0.01 percent

FARM TRUCKS

The vehicle registration system in Texas distinguishes a category, "farm truck," which is subject to only half the normal registration fee. In 1998, there were about 200,000 vehicles registered in this category, which includes trucks carrying livestock, livestock products, and timber. Because the Texas sample in the VIUS was too small for us to reliably allocate farm trucks among vehicle classes, we relied on the national sample. For trucks mainly used for agriculture or forestry and lumbering, we estimated the percentage breakdown between combination and single-unit trucks and among the single-unit classes. At five percent, the combination truck share of these "farm" trucks was too small to be accurately broken down by vehicle class; hence, we assumed farm trucks to form the same percentage of each combination class. For all truck classes, we assumed that farm trucks have the same registered weight distributions as other trucks.

ESTIMATION: GOVERNMENT-OWNED VEHICLES

For passenger cars, we took from *Highway Statistics, 1998* the number of Texas-registered vehicles by category of owner: private, federal, or state/local government. For trucks, we calculated from the same source the percent distribution of Texas nonfarm vehicles among these same ownership categories. (Farm vehicles are private.) The number of government-owned transit buses in Texas was estimated in the manner already described. In all cases, the distribution of vehicles according to weight and other characteristics was assumed to be independent of the type of owner.

Table N.6. Percent distribution of combination trucks by operating weight and vehicle class, Texas 1998

	4 Ax-STT	**5 Ax STT**	**6 Ax+ STT**	**5 Ax-MTT**	**6 Ax MTT**	**7 Ax+ MTT**
weight (000s lbs)						
under 10	1.51	0.00	0.00	0.00	0.00	0.00
10–15	12.41	0.02	0.00	0.00	0.00	0.00
15–20	14.94	0.73	1.59	1.01	7.55	0.00
20–25	17.06	2.13	1.49	3.30	0.53	0.79
25–30	14.96	4.48	4.08	5.36	2.05	1.80
30–35	14.15	8.45	10.54	5.39	4.77	2.49
35–40	10.74	10.51	10.78	5.32	7.11	4.72
40–45	6.90	6.76	8.92	5.88	8.44	7.66
45–50	3.71	6.23	7.11	7.66	8.71	7.50
50–55	2.16	5.17	5.53	9.27	9.55	6.55
55–60	0.98	4.81	4.94	12.04	10.70	7.97
60–65	0.30	5.84	4.96	11.10	10.28	8.22
65–70	0.10	8.29	5.43	10.94	9.21	8.67
70–75	0.04	9.23	5.80	9.44	7.67	6.98
75–80	0.03	26.44	20.41	13.07	10.63	5.74
80–85	…	0.40	0.59	…	0.20	0.31
85–90	…	0.37	1.95	0.06	0.54	1.19
90–95	0.00	0.03	0.70	0.00	0.63	0.18
95–100	0.00	0.06	1.79	…	0.36	0.11
100–105	0.00	0.02	0.72	0.01	0.27	7.43
105–110	0.00	0.02	0.73	0.15	0.65	12.71
110–115	0.00	0.00	0.41	0.00	0.03	0.96
115–120	0.00	0.00	1.34	0.00	0.06	1.06
120–125	0.00	0.00	0.03	0.00	0.02	0.94
125–130	0.00	0.00	0.05	0.00	0.05	1.23
130–135	0.00	0.00	0.12	0.00	0.00	0.04
135–140	0.00	0.00	0.00	0.00	0.00	0.18
140–145	0.00	0.00	0.00	0.00	0.00	1.11
145–150	0.00	0.00	0.00	0.00	0.00	3.47

NOTE: Column totals may not add exactly to 100 because of rounding

… less than 0.01 percent

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