FHWA-NJ-2001-030

Infrastructure Costs Attributable to Commercial Vehicles

FINAL REPORT
December 2001

Submitted by

Dr. Maria Boilé*
Assistant Professor

Dr. Kaan Ozbay*
Assistant Professor

Ms. Preethi Narayanan*
Graduate Research Assistant

* Dept. of Civil & Environmental Engineering
Center for Advanced Infrastructure & Transportation (CAIT)
Rutgers, The State University
Piscataway, NJ 08854-8014

NJDOT Research Project Manager
Mr. Edward Kondrath

In cooperation with

New Jersey
Department of Transportation
Division of Research and Technology
and
U.S. Department of Transportation
Federal Highway Administration

DISCLAIMER STATEMENT

TECHNICAL REPORT

1. Report No. FHWA-NJ-2001-030	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Infrastructure Costs Attributable to Commercial Vehicles	5. Report Date December 2001
	6. Performing Organization Code CAIT/Rutgers
7. Author(s) Dr. Maria Boilé, Dr. Kaan Ozbay, Ms. Preethi Narayanan	8. Performing Organization Report No. FHWA-NJ-2001-030
9. Performing Organization Name and Address New Jersey Department of Transportation PO 600 Trenton, NJ 08625	10. Work Unit No.
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address New Jersey Transit Newark, New Jersey	13. Type of Report and Period Covered Final Report 1/1/2001 - 31/12/2001
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report pertains to a comprehensive study on infrastructure costs attributable to heavy vehicles. This study has two primary objectives. The first is to review pertinent literature and determine the availability of methods for allocating roadway maintenance costs to different types of vehicle classes. The second objective is to determine the existence and availability of methodologies to estimate the impact of different types of buses on highway infrastructure. Two broad areas of highway impact related literature have been reviewed. The first one, namely highway cost allocation studies, deals primarily with the first objective, of estimating highway related costs attributable to heavy vehicles. The second area deals with the development of models to estimate pavement deterioration as a result of vehicle-pavement interactions. A federal, and several state highway cost allocation studies have been reviewed. These studies vary in their data requirements, ease of use and update, and output detail, which are parameters that need to be considered in selecting the most appropriate method for New Jersey applications. A cost allocation study has not been performed for the state of New Jersey. Performing such a study, however, would be highly recommended, since it helps develop a clear picture of the cost responsibility of each vehicle class and decide whether changes need to be made in order to charge each vehicle class its fair share of cost responsibility. A thorough consideration should be given to New Jersey specific conditions and requirements prior to developing a state highway cost allocation model. Whether a simplified or a more detailed approach is used, high levels of data accuracy and state specific conditions will help increase the accuracy of model results. In that sense, a simplified approach well tailored to New Jersey conditions is expected to produce more accurate results, compared to a more detailed approach, based on default data. The first part of the study provided very limited information on the impact of different types of buses on highways. After a thorough literature search and contacts with state DOTs and local authorities only two studies were found to deal explicitly with the impact of buses on pavements. Based on these studies and a review of data availability in New Jersey, a proposed method has been developed. A step-by-step guide on how to apply this method along with data requirements is given in this report.

17. Key Words Highway Cost Allocation Study, Highway Infrastructure Costs, Pavement Deterioration, Bus Transit, Axle Loads	18. Distribution Statement

19. Security Classif (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No of Pages 66	22. Price

Form DOT F 1700.7 (8-69)

Acknowledgements

The authors wish to express their appreciation to the New Jersey Department of Transportation for the allotment of funds making this research possible. The authors would also like to thank Mr. Thomas Bennert of Rutgers University, Rutgers Asphalt Pavement Laboratory for his effort on the pavement section analysis portion of this report.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

List of Abbreviations and Symbols

3R	Pavement Reconstruction, Rehabilitation, and Resurfacing
AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
Arizona SMHCAS	Arizona Simplified Model for Highway Cost Allocation Studies
BSAIR	Bitumen Structures Analysis in Roads
DEM	Distinct Element Method
DOT	Department of Transportation
EALF	Equivalent Axle Load Factor
ESAL	Equivalent Single Axle Load
FEM	Finite Element Method
FHCAS	Federal Highway Cost Allocation Study
FHWA	Federal Highway Administration
FMIS	Financial Management Information System
HCAS	Highway Cost Allocation Study
HDM	Highway Design and Maintenance Standards Model
HPMS	Highway Performance Monitoring System
IMS	Information Management System
LEA	Layer Elastic Analysis
LEF	Load Equivalency Factor
LTPP	Long Term Pavement Performance
MET	Method of Equivalent Thickness
MMOPP	Mathematical Model of Pavement Performance
NAPCOM	Nationwide Pavement Cost Model
NJDOT	New Jersey Department of Transportation
PCE	Passenger Car Equivalent
PMS	Pavement Management System
PSI	Pavement Serviceability Index
SHRP	Strategic Highway Research Program
SN	Structural Number
STIP	State Transportation Improvement Program
TPI	Truck Pavement Interaction
TS & W Study	Truck Size and Weight Study
US DOT	United States Department of Transportation
VMT	Vehicle Miles Traveled

ABSTRACT

This report pertains to a comprehensive study on infrastructure costs attributable to heavy vehicles. This study has two primary objectives. The first is to review pertinent literature and determine the availability of methods for allocating roadway maintenance costs to different types of vehicle classes. It examines the application of these methods to estimating roadway maintenance costs attributable to bus and truck traffic in New Jersey, along with the availability and appropriateness of existing data. The second objective is to determine the existence and availability of methodologies to estimate the impact of different types of buses on highway infrastructure. Two broad areas of highway impact related literature have been reviewed. The first one, namely highway cost allocation studies, deals primarily with the first objective, of estimating highway related costs attributable to heavy vehicles. The second area deals with the development of models to estimate pavement deterioration as a result of vehicle-pavement interactions.

A federal, and several state highway cost allocation studies have been reviewed. These studies vary in their data requirements, ease of use and update, and output detail, which are parameters that need to be considered in selecting the most appropriate method for New Jersey applications. A cost allocation study has not been performed for the state of New Jersey. Performing such a study, however, would be highly recommended, since it helps develop a clear picture of the cost responsibility of each vehicle class and decide whether changes need to be made in order to charge each vehicle class its fair share of cost responsibility. A thorough consideration should be given to New Jersey specific conditions and requirements prior to developing any state highway cost allocation model. Whether a simplified or a more detailed approach is used, high levels of data accuracy and state specific conditions will help increase the accuracy of model results. In that sense, a simplified approach well tailored to New Jersey conditions is expected to produce more accurate results, compared to a more detailed approach, based on default data.

The first part of the study provided very limited information on the impact of different types of buses on highways. After a thorough literature search and contacts with state DOTs and local authorities only two studies were found to deal explicitly with the impact of buses on pavements. Based on these studies and a review of data availability in New Jersey, a method has been developed. A step-by-step guide on how to apply this method along with data requirements is given in this report.

INTRODUCTION

The highway system forms the backbone of the United Sates with over 46,000 miles of Interstate highways, 113,757 miles of other National Highway System roads and 3,760,876 miles of other roads. Careful planning considerations and alternatives analysis as well as educated investment decisions are necessary to maintain the nation's infrastructure in a sound condition to support the level of operations and provide the degree of serviceability they were designed to handle.

Highway related expenditures may be broadly classified as either agency costs or user costs. Agency costs include initial construction, future rehabilitation and preventive maintenance, project overhead, and traffic control. User costs include vehicle operation, user delay, and crash costs. [1] Factors that can affect these costs are the materials selected for particular types of construction, the initial design, current and future traffic, and maintenance and rehabilitation practices. Careful estimation of these components of agency and user costs presents a major challenge to transportation planners since some of the cost components are not easy to quantify and their interactions are not always easy to establish.

The primary objective of this project is to review pertinent literature and determine the availability of methods for allocating roadway maintenance costs to different types of vehicle classes. The application of these methods to estimating roadway maintenance costs attributable to bus and truck traffic in New Jersey, along with the availability and appropriateness of existing data will also be examined. As the work on the project progressed and based on a discussion with the project customer, another objective was identified, namely to determine the existence and availability of methodologies to estimate the impact of different types of buses on highway infrastructure.

To address these objectives, two broad areas of highway impact related literature were reviewed. The first one, namely highway cost allocation studies, dealt primarily with the first objective, of estimating highway related costs attributable to heavy vehicles. This area provided very limited information on the impact of different types of buses on highways. Review of highway cost allocation studies and summary of the findings is presented in the following section. The second area of literature that was reviewed deals with the development of models to estimate pavement deterioration as a result of vehicle-pavement interactions. Results are presented in the third section. Most of the literature in this area deals with the impact of trucks on pavements. The fourth section reviews studies that explicitly treat the impact of buses on highway infrastructure. The fifth section outlines a proposed methodology for estimating the impact of various types of buses on New Jersey highways and the associated data requirements. Finally, the last section summarizes the major findings and conclusions of this study.

HIGHWAY COST ALLOCATION STUDIES

Highway related expenditures may be broadly classified as either agency costs or user costs. Agency costs include initial construction, future rehabilitation and preventive maintenance, project overhead, and traffic control. User costs include vehicle operation, user delay, and crash costs. [1] On the agency cost side, state departments of transportation allocate 40% or more of their annual budgets to pavement maintenance and rehabilitation projects. Information on pavement condition, costs and revenues is reported annually to the FHWA Highway Statistics program by each state.

To determine the infrastructure cost responsibility of various vehicle classes, Highway Cost Allocation Studies (HCAS) are being conducted by the Federal and several State Departments of Transportation (DOTs). In these studies, agency costs are allocated to various vehicle classes based on the vehicle's impacts on pavement and traffic condition. The primary focus of this study is on pavement maintenance costs, the major part of which is attributable to heavy vehicles. Although HCASs have been performed for many years, cost responsibility of vehicle classes is still an evolving field and there are no established standards to ascertain vehicle cost-responsibilities.

A detailed discussion of HCAS concepts is presented in [2] and summarised herein. A HCAS is an attempt to compare revenues collected from various highway users, to the expenses incurred by highway agencies in providing and maintaining facilities for these users. The basic premise behind HCAS is that highway users should pay an amount sufficient to cover at least part of the cost incurred by highway agencies in providing and maintaining these facilities. Likewise, highway users should not be forced to pay more than what it costs the agencies to provide the required facilities.

Highway cost allocation studies has been devised to resolve the complicated distribution of revenues and expenses among different groups of highway users. These studies assess the equity of the existing highway user tax structure and determine whether changes in that structure are needed. Highway user taxes, however, are generally collected through indirect means such as taxation of fuel or vehicle value and not through direct charges for roadway usage, which makes determination of equity a complicated endeavour.

Highway users are grouped according to such variables as vehicle type, vehicle weight, commercial and non-commercial status, etc., to estimate the expenses that each group imposes on the highway system and the revenues that each group generates. The expenditure side of the HCAS equation includes all actual planned and estimated expenditures for roads (including overhead), regardless of the source of the funds. These expenditures represent what it costs to serve the needs of highway users. The cost allocation study does not evaluate how much money should be spent on highways. It merely allocates responsibility to various classes of highway users for the amount of money that government agencies spend on highways.

Historical Overview of Highway Cost Allocation Studies

Today, the Federal highway construction program and most State highway programs are financed primarily from various taxes and fees imposed on highway users. Until 1932 federal Highway programs were financed entirely from general revenues. In 1932 the federal government imposed taxes on gasoline fuel, the revenue from which was formally earmarked for highway programs when the highway trust fund was created in 1956.

In the interval, the states which had led the way in imposing gasoline taxes and which had also introduced vehicle registration fees, took a closer look at the allocation of pavement-wear costs between trucks and autos.

Following World War II, eleven states adopted “third-structure” taxes, which attempted to assess heavy vehicles according to their total weight and distance travelled. Research had found that, due to their weight, heavy vehicles are the primary contributors to pavement damage. Although they consume more fuel than light vehicles, the fuel taxes still were not able to account for the heavy vehicle cost-responsibility.

The Federal Government and about half the States conducted HCASs over the last several decades. In 1956 and again in 1978 Congress mandated that Federal HCASs be conducted to evaluate the equity of the Federal highway user fee structure. The 1978 mandate also required that alternative highway user fee structures be evaluated to identify options that could improve overall user fee equity and bring user fee payments by each class closer to the user's highway cost responsibility. In general, the closer the match between user fees and highway cost responsibilities for each vehicle class the more equitable the user fee structure. [1]

General Overview

Highway Cost Allocation Studies use various different approaches to allocate costs. The four main approaches are:

Cost-occasioned approach: physical and operational characteristics of each vehicle class are related to expenditures for pavement, bridge, and other infrastructure improvements.

Benefit based approach: costs are allocated according to the relative benefits realized by different vehicle classes from highway investments. The greater the benefits, the greater the share of user fees a vehicle class should pay, regardless of its contribution to highway costs.

Marginal cost approach: vehicles are charged according to environmental, congestion, pavement, and other marginal costs associated with their highway use. Unlike other approaches, the objective of the marginal cost approach is not to assign all highway agency expenditures to different vehicle classes, but rather to estimate user fees that would cover marginal costs of highway use by different vehicle classes. However, the marginal cost approach could be adapted to recover full agency costs. Neither the benefits approach nor the marginal cost approach has ever been completely applied in a major study.

Incremental approach: pavement construction and rehabilitation costs are essentially allocated in the same way. The cost of required basic pavement thickness is allocated to all vehicles based on VMT. The extra thickness required due to heavy vehicle traffic is allocated based on ESAL (standard 18-kip single axle load) or VMT weighted ESAL.

The four approaches differ in their methodology in allocating costs; they are similar however, in that they allocate expenditures and revenues to different vehicle classes in proportion to some measure of consumption and benefits like PCE, VMT or ESAL. Revenues and expenditure for each vehicle class are then compared, to determine whether each vehicle class is paying its correct share of cost responsibility. If not, then recommendations are made to rectify the inequity.

All recent Federal and State Highway Cost Allocation Studies use the cost-occasioned approach. The latest Federal and some State Highway Cost Allocation studies will be reviewed and compared in the following sections.

Federal Highway Cost Allocation Study (FHCAS)

The FHCAS 1997 [3] is the latest FHCAS. The base period for this study is 1993-1995 and the analysis year is 2000. Base year distributions of highway program costs by improvement type represent an average of obligations over the 1993-1995 period. Base year revenues are averaged over the 1993-1995 period as well. The primary source of cost data is FHWA's Financial Management Information System (FMIS), which contains information on FHWA obligations for Federal-aid highway projects, direct Federal projects, and all other purposes.

Highway cost responsibility is strongly influenced by a vehicle's axle configuration and axle weights. The U.S. DOT Comprehensive Truck Size and Weight (TS&W) Study evaluates many potential vehicle configurations and gross weights. For the purpose of highway revenue and cost analyses, however, the FHCAS considers 20 broad vehicle classes. Table 1 lists the vehicle classes, their acronyms and a brief description of the types of vehicles included in each class. Figure 1 presents a graphical image of the axle configuration for each vehicle class.

Highway cost responsibility is estimated for up to thirty 5,000-lb. weight intervals for each vehicle class. Weights range from 5,000 lbs. or less to more than 145,000 lbs.

In addition to vehicle type and weight, cost responsibility is also related to the nature and location of highway improvements and to the location of travel by different vehicle classes. Location is accounted for by estimating vehicle travel and related cost responsibilities for 12 functional classes of highways. These classes are shown in Table 2.

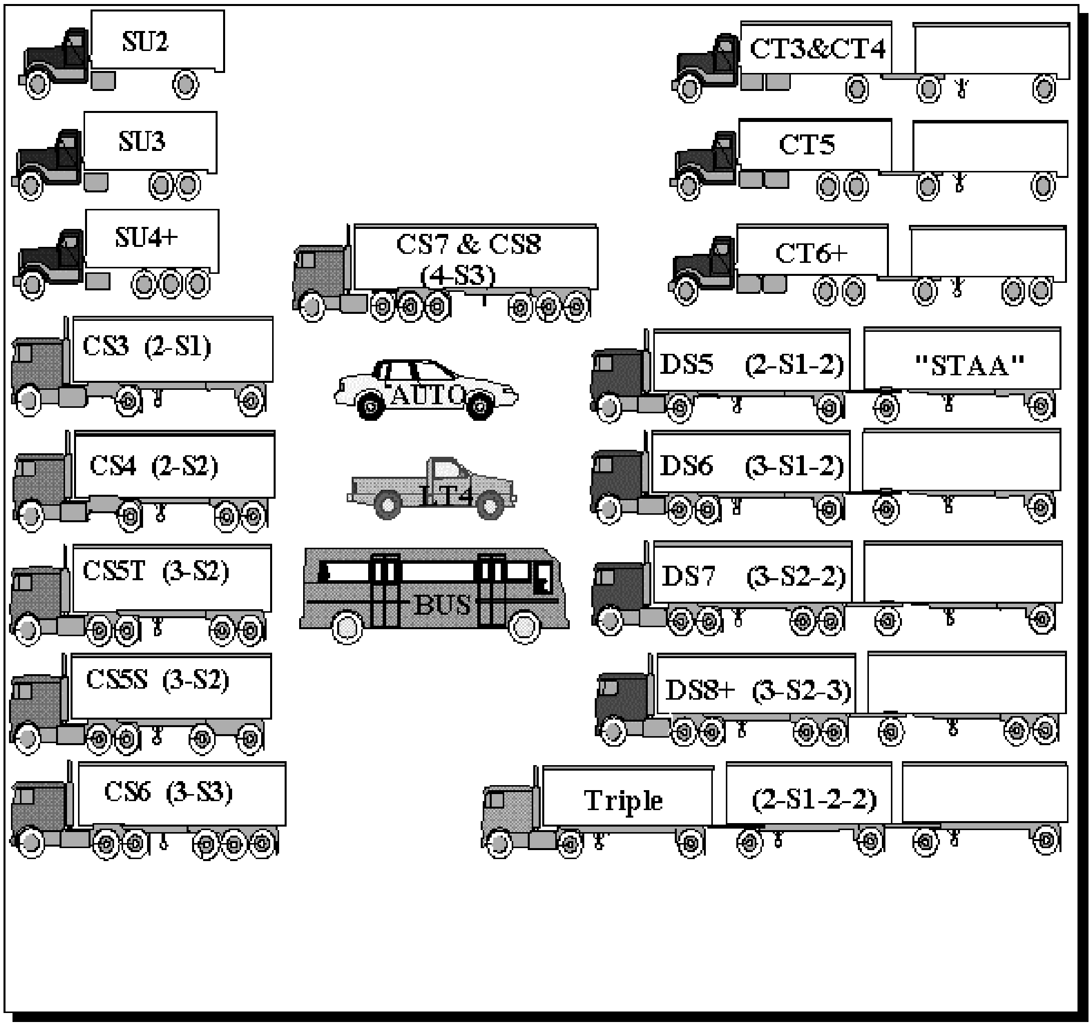
Costs related to the need for new highway capacity are allocated to vehicles on the basis of vehicle miles travelled (VMT) weighted by a passenger car equivalent factor (PCE), a measure used to compare the influence of different types of vehicles on highway capacity.

Costs for the additional pavement thickness, to accommodate projected vehicle loading, is allocated based on the relative Equivalent Single Axle Load (ESAL) of each vehicle class. Pavement design equations developed by AASHTO use ESALs as the principal vehicle specific factor in pavement design. Separate allocations are made for rigid and flexible pavement types. The ESAL methodology is reviewed in more detail in Appendix 1.

Table 1 HCAS Vehicle Class Categories

VC	Acronym	Description
1	AUTO	Automobiles and Motorcycles
2	LT4	Light trucks with 2-axles and 4 tires (Pickup Trucks, Vans, Minivans, etc.)
3	SU2	Single unit, 2-axle, 6 tire trucks (includes SU2 pulling a utility trailer)
4	SU3	Single unit, 3-axle trucks (includes SU3 pulling a utility trailer)
5	SU4+	Single unit trucks with 4- or more axles (includes SU4+ pulling a utility trailer)
6	CS3	Tractor-semi trailer combinations with 3-axles
7	CS4	Tractor-semi trailer combinations with 4-axles
8	CS5T	Tractor-semi trailer combinations with 5-axles, two rear tandem axles
9	CS5S	Tractor-semi trailer combinations with 5-axles, two split (>8 feet) rear axles
10	CS6	Tractor-semi trailer combinations with 6-axles
11	CS7+	Tractor-semi trailer combinations with 7- or more axles
12	CT34	Truck-trailers combinations with 3- or 4-axles
13	CT5	Truck-trailers combinations with 5-axles
14	CT6+	Truck-trailers combinations with 6- or more axles
15	DS5	Tractor-double semi trailer combinations with 5-axles
16	DS6	Tractor-double semi trailer combinations with 6-axles
17	DS7	Tractor-double semi trailer combinations with 7-axles
18	DS8+	Tractor-double semi trailer combinations with 8- or more axles
19	TRPL	Tractor-triple semi trailer or truck-double semi trailer combinations
20	BUS	Buses (all types)

Source: 1997 Federal Highway Cost Allocation Study



Source: 1997 Federal Highway Cost Allocation Study

Figure 1 Graphical Illustration of HCAS Vehicle Classes

Table 2 Highway Functional Classes

Rural	Urban
Interstate	Interstate
Other Principal Arterials	Other Freeways and
Minor Arterials	Other Principal Arterials
Major Collectors	Minor Arterials
Minor Collectors	Collectors
Local	Local

Source: 1997 Federal Highway Cost Allocation Study

Costs for pavement reconstruction, rehabilitation, and resurfacing (3R) are allocated to different vehicle classes on the basis of each vehicle's estimated contribution to pavement distresses necessitating the improvements. An important contribution of the 1982 Federal HCAS was the use of "mechanistic" pavement distress models that directly relate axle loads and repetitions to the stresses, strains, and other pavement responses leading to pavement deterioration. Several mechanistic models used in the 1982 Federal HCAS have been retained in the new pavement cost approach, but most models have been improved based upon new theoretical work and the availability of pavement performance data from the Long Term Pavement Performance (LTPP) Study. Eleven different pavement distress models are incorporated in the new nation-wide pavement cost model (NAPCOM) used for FHCAS. These models represent the state-of-the-art in predicting pavement responses to different axle loads and repetitions.

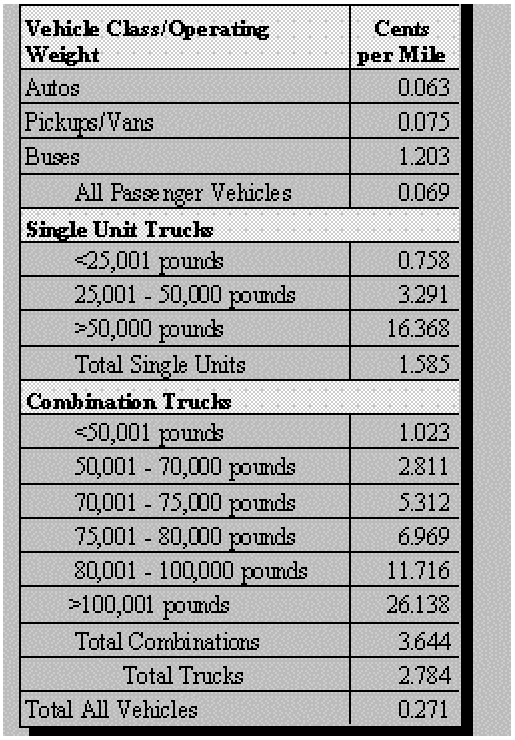
The Federal HCAS analysed pavement distresses on actual pavement sections included in the Highway Performance Monitoring System (HPMS) database. The HPMS database is a statistically valid sample of over 100,000 pavement sections representing all non-local pavements nation-wide.

While the HPMS database contains section properties, traffic volumes, percent trucks and other data related to pavement performance, considerable supplemental data needed for the pavement performance models were added for each pavement section. Estimates of the relative cost responsibility of different vehicle classes for pavement 3R costs on the different highway functional classes are used to allocate load-related components of 3R obligations to the different vehicles. The models also estimate the shares of total costs that are related to factors such as pavement age and climate rather than axle loads. These non load-related 3R costs are allocated in proportion to VMT for each vehicle class.

In general, the share of costs attributable to non-load factors is about the same for flexible and rigid pavements, although there are minor differences across highway functional classes. Non-load costs are a higher proportion of total costs on lower-order systems than on higher-order systems, ranging from less than 10 percent on rural Interstates to more than 20 percent on urban collectors and local roads.

A summary of the 1997 FHCAS results on cost responsibilities for 3R-pavement improvement by vehicle class and operating weight range is shown in Table 3. Cost responsibility increases at an increasing rate as the weight of each vehicle class increases. Single axles contribute more to 3R pavement costs than tandem axles, and tandem axles contribute more than tridem axles for vehicles with comparable weights.

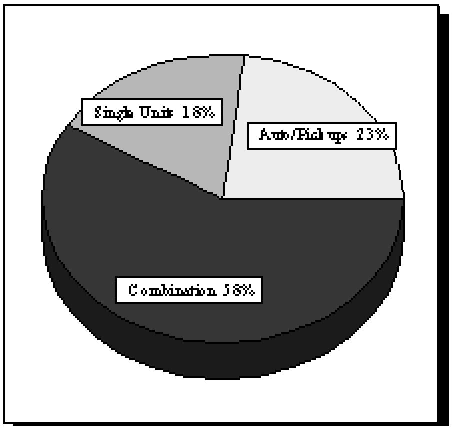
Table 3 Federal Cost Responsibility for 3R Pavement Improvement



Vehicle Class/Operating Weight	Cents per Mile
Autos	0.063
Pickups/Vans	0.075
Buses	1.203
All Passenger Vehicles	0.069
Single Unit Trucks	
<25,001 pounds	0.758
25,001 - 50,000 pounds	3.291
>50,000 pounds	16.368
Total Single Units	1.585
Combination Trucks	
<50,001 pounds	1.023
50,001 - 70,000 pounds	2.811
70,001 - 75,000 pounds	5.312
75,001 - 80,000 pounds	6.969
80,001 - 100,000 pounds	11.716
>100,001 pounds	26.138
Total Combinations	3.644
Total Trucks	2.784
Total All Vehicles	0.271

Source: 1997 Federal Highway Cost Allocation Study

Figure 2 shows the overall distribution of pavement 3R cost responsibility among all passenger vehicles, single unit trucks, and combination trucks according to the 1997 HCAS.



Source: 1997 Federal Highway Cost Allocation Study

Figure 2 Federal 3R Cost Responsibility Distribution by Broad Vehicle Classes

The allocation of basic new pavement and non-load related costs by VMT weighted by PCE is logically correct as vehicles pay for new infrastructure based on their requirement and usage of the facility. The allocation of load-related pavement cost based on ESAL is logical and makes the allocation method straight forward as the ESAL estimates for the FHWA vehicle classes are already available from the pavement design stage.

State Highway Cost Allocation Study by FHWA

A spreadsheet-based highway cost allocation model [4] has been developed by Federal Highway Administration to provide guidelines and facilitate state highway cost allocation studies. The state model is partly based on the work conducted by the Federal Highway Administration for the 1997 Federal Highway Cost Allocation Study, it is however more flexible than FHCAS. More specifically, the common cost for new pavement can be allocated by VMT, or PCE, or a combination of both, or by the pavement deterioration method, depending on user's choice. The cost for extra pavement thickness required to accommodate heavy vehicles is allocated to vehicles depending on their ESAL, which is the same approach as the one followed in the FHCAS. The non-load related pavement rehabilitation cost, which is the cost due to climate, ageing etc., is allocated the same way as the common cost for new pavement. The load-related pavement rehabilitation cost, which accounts for 70 to 80 percent of the total pavement rehabilitation cost, is allocated on the basis of ESALs instead of using the FHCAS's NAPCOM model. The reason for not using the NAPCOM model is explained in the Highway Cost Allocation Guidelines: [4]

"NAPCOM does not use ESALs at all, instead it is estimating the rate of progression of individual types of pavement distress under given pavement design, traffic, and environmental conditions. Because most of the distresses included in NAPCOM results from an interaction between axle loads and environmental conditions (axle loads cause more pavement rutting, for example, on hot pavements), NAPCOM finds far lower (but highly variable) non-load percentages of costs. As applied at the national level, NAPCOM did not have access to pavement section data for Urban or Rural Local roads or for Rural Minor Collectors, but would probably have found higher non-load-related shares for these lower level road systems. Similarly, the set of pavement sections used in NAPCOM for any particular state, as applied at the national level, provided too small a sample for a conclusive estimate of the non-load share for that state. Enhancing the sample and the related design and environmental data could substantially improve the accuracy of the estimates for any given state."

The pavement maintenance expenditures are broken down into specific maintenance activities and highway type, and are allocated by VMT, PCE, ESAL or other vehicle characteristics depending on the chosen criteria. Additional research is required, to determine the best criteria to allocate a specific type of maintenance cost.

Conceptual Application of the State Highway Cost Allocation Model

The data requirements for the spreadsheet model application to any state are very extensive. Default data sets based on the FHCAS are provided, however, before applying the model, these default data sets must be thoroughly reviewed and analysed, to verify their accuracy with regard to any particular state's conditions. All the default data available with this model are only representative values and cannot be used to derive conclusions. State specific information should be used whenever available.

The cost allocation part of this model handles four pavement cost categories: new flexible pavements, new rigid pavements, flexible pavement repair and reconstruction, and rigid pavement repair and reconstruction, each of which should be broken down into the standard 12 functional classes of highway (or other types of highway classes), and by any special funding categories the user wishes to analyse. The required expenditure data needs to be collected for the state of interest. Some of the required data is typically available through State Transportation Improvement Programs (STIP).

The most important criteria for allocating costs are the annual Vehicle Miles of Travel. State wide annual VMT for the state of interest must be estimated and be broken down into the following categories:

- Vehicle configuration
- Registered gross weight
- Fuel type
- Functional class of highway or other user-specified highway classes

The document recommends the data compiled for the Highway Performance Monitoring System (HPMS), which is reported each year by states to the Federal Highway Administration (FHWA) should be the primary source of basic VMT information. These data generally includes VMT by 12 vehicle configurations (13 if motorcycles are separated out) and 12 highway functional classes.

Some states may not have all the breakdowns required, such as splits of VMT for single unit trucks broken down into two, three, and four or more axles, or splits of combinations into all of the standard seven classes of combinations. In such cases, a state's VMT for larger classes can be disaggregated into the more detailed classes using data from other neighbouring states or states with similar economies and other characteristics, obtained from the Federal Highway Administration.

Additional inputs required for state pavement cost allocation include:

- Operating gross weight distributions by vehicle configuration (and optionally by highway class)
- Axle weight and axle type frequency distributions for each operating weight and vehicle class
- Typical pavement sections and traffic proportions that represent the flexible and rigid pavements for each highway class

- Number of miles on each highway class (to determine average daily traffic loading from VMT data), for new pavement cost allocation
- Annual equivalent single axle load (ESAL) growth rates by highway class, for new pavement cost allocation
- Pavement design parameters applicable to the state in question, for new pavement cost allocation
- Minimum pavement thickness, for rigid and flexible pavements
- Pavement distress distributions and load equivalency factor (LEF) regression coefficients for each highway class, for pavement rehabilitation cost allocation
- A conversion key, if necessary, to convert state-specified highway classes to the 12 highway functional classes

Finally, in addition to the above data, maintenance cost allocation requires:
- Expenditures for different categories of maintenance work broken down by highway class: travel-related maintenance, wear-related flexible pavement maintenance, wear-related rigid pavement maintenance, axle-related maintenance, truck-mile-related maintenance, light-vehicle-related maintenance, and rest-area maintenance
- Specification of allocating criteria for each of these cost categories.

These data are typically available, since most states maintain a detailed record of their maintenance activities.

The spreadsheet model was run with the default data set for various states. For some of these states, including New Jersey, the model did not function correctly and gave an error message. During debugging it was noticed that the error was caused due to lack of data for these states.

A thorough review of the model shows that:
- The model is very detailed and comprehensive for allocation of pavement costs specifically at the state level.
- The data requirements are very high.
- Default data for some states are not available.
- Even if data are available, it might not be in the form required for the model and thus a lot of time would be spent on breaking them down to the required categories.
- This model does not use mechanized pavement models, which are more accurate in predicting pavement damage.

Long before this model was developed by the FHWA for state applications, various states had already developed Highway Cost Allocation Models that best suited their requirements and environment. Some of these studies have been reviewed in the following sections.

Highway Cost Allocation Studies by States

The Arizona Simplified Model for Highway Cost Allocation Studies

The Arizona Simplified Model for Highway Cost Allocation Studies (Arizona SMHCAS) [2] was developed in 1999 as an alternative to the complicated model for highway cost allocation previously used by Arizona Department of Transportation.

The Arizona SMHCAS is contained within a single Excel spreadsheet workbook that fits on a standard 3½-inch floppy disk. All equations and calculations are visible to the operator, and can be modified to suit future changes in spending or taxation. Worksheets are grouped according to functional categories: Inputs, Adjustment Factors, Reference Files and Outputs. In accordance with the goal of providing a portable, easy-to-use model, the SMHCAS contains no macros, external references, algorithms or other complications. All calculations are made using standard Excel formulas and internal look-up references.

The Arizona SMHCAS differs from other highway cost allocation models primarily in its treatment of expenditures. Whereas revenues are distributed in similar ways in the FHCAS, the old Arizona HCAS and the Arizona SMHCAS models, cost responsibility distribution in the SMHCAS is far less complicated than in the other two models. The SMHCAS allocation of expenditures is based on the following two premises:

Capital expenditures in urbanized areas are primarily the result of the need for additional *capacity*. Any construction on highway segments in an urbanized area will therefore be allocated according to an unadjusted share of highway usage (i.e. vehicle miles of travel). Based on a consensus in the literature regarding allocation of capacity-driven expenditures, passenger car equivalency factors (PCEs) were added as an option for allocating cost responsibility in urbanized areas.

Capital expenditures on highway segments outside of urban areas are considered in terms of added *strength* (thickness) required for heavier vehicles. The share of VMT on these segments is therefore weighted in accordance with standardized equivalent single axle loads (ESALs) prior to allocation of cost responsibility.

Based on these two premises, the data requirements are as follows:

- Urban VMT distribution
- Rural VMT distribution
- Registration of various vehicle classes

Expenditures: construction, maintenance, administrartive and others for rural and urban roads respectivelly

The expenditures data are compiled in three categories: "Capacity-driven" expenditures, "Strength-driven" expenditures, and "Common" costs such as Arizona DOT's overhead and operating expenses. Expenditure data from different levels of government are allocated to each category based on different methods, depending on the manner in which the source data are presented. The allocation methods for each category and data source are indicated in the following table.

Table 4 Allocation Methods by Level of Government and Type of Expenditure

Allocation Method	State Level [1.]	Local Levels [2.]	
		Metropolitan Areas [3.]	Counties
Capacity	Spending Program Share (Urban)	Construction estimates for Cities & Towns; Regional government expenditures	---
Strength	Spending Program Share (Rural)	Maintenance (pavement)	Construction estimates for Counties; Maintenance (pavement)
Common	Overhead and Administration; Highway Patrol and Safety; Spending Program Share	Administration and Safety; Interest on Debt; Road and Street Services; Maintenance (non-pavement)	Administration and Safety; Interest on Debt; Road and Street Services; Maintenance (non-pavement)
Notes	1. Includes federally funded portion of the state Spending Program forecast. 2. Includes expenditures funded by transfers from state and federal sources. 3. Local Government reports for cities and towns, counties and regional governments.		

Source: Report on Simplified Arizona Highway Cost Allocation Study Model (*2)*

Of the three methods for allocating cost responsibility, the means of distributing Capacity-driven and Common expenditures are similar. Both types of expenditures are distributed among vehicle and weight classes according to their share of VMT. However, capacity-driven expenditures are distributed according to *urban* VMT only, whereas common expenditures are distributed according to total VMT. Strength-driven highway expenditures are allocated according to the share of *rural* VMT applicable to each vehicle or weight class, but are adjusted by equivalent single axle load (ESAL) factors for each configuration and weight class. While it is likely that some of these expenditures on rural segments are driven by the need for capacity (and that some urban segment expenditures are a function of added strength and width requirements), the adverse effect of axle loading has been shown to have a greater impact on the flexible pavements common on rural highways than on the rigid concrete of urban freeways.

The new SMHCAS was back-tested against results obtained by the older SYDEC model used by the Arizona Department of Transportation. The output results of both models were examined to determine whether the simplicity of the SMHCAS had a detrimental effect on its accuracy relative to the more complicated SYDEC model. While some variance in output results was observed, the overall SMHCAS outputs were generally quite close to those of the older model.

Oregon Cost Allocation Study

Oregon has a long history of conducting cost-responsibility studies and basing its system of road user taxation on the results of these studies. The first cost-responsibility study in Oregon was conducted in 1937 and the latest in 1998. [5] The rest of this section is a review of the 1998 study.

This study follows the FHCAS. The common pavement costs are allocated by VMT while the load-related pavement costs are allocated using the NAPCOM model.

The construction expenditure data required for fiscal year 2000-2001 is obtained by extrapolating data from 1998-2001 STIP. Maintenance and other program expenditures were developed by ODOT based upon current budget estimates. Expenditures for every highway project, modernization and preservation programs included in the 1998-2001 STIP were also considered. The data were broken down into the various categories required for cost allocation procedures.

Historical data and assumptions used in the 1998 State wide Congestion Overview for Oregon and a revenue forecasting model were used in combination to forecast calendar year 2000 revenue data from base-year (1998) data.

Indiana Highway Cost Allocation Study

The Indiana Highway Cost Study [6] was conducted in 1983 and was updated in 1988. In this study the highway expenditures were documented by jurisdictional system, then by highway functional class and finally by expenditure area and expenditure item. The two jurisdictional systems are state highway and local highway system. The total state highway system expenditure was divided into three functional classes: Interstate highways, state primary and state secondary routes. The total expenditure on local highway system was classified into county roads and city streets. Six expenditure areas and a number of expenditure items were identified for each of these functional classes. Such a detailed classification of highway expenditures was necessary because each of the expenditure items have different cost responsibility for a given vehicle group.

The data requirements are quite extensive. [7] Pavement inventory data included pavement characteristics, roadway geometry and highway functional classification. These data were obtained from road life records and construction reports kept by the Indiana DOT. Pavement performance data are required in pavement maintenance and rehabilitation cost responsibility computations. For this study, the pavement performance of each pavement analysed was derived from its roughness history. Indiana DOT maintains annual roadmeter records for the pavement. These roughness measures were converted into present serviceability index (PSI) values by means of roughness-PSI correlation models.

Traffic data was needed for computing traffic loading in terms of ESAL for the allocation analysis of pavement costs. Data was collected on the field. In this study vehicles were grouped into 14 classes with Bus being one of the classes. Cost responsibility for each vehicle class was computed separately for each highway class. In case where cost responsibilities were affected by pavement type, separate cost responsibility factors were also developed for each pavement type.

Pavement routine maintenance and rehabilitation costs represent a large portion of the total highway maintenance and rehabilitation expenditure in Indiana. Pavement costs computation was based on pavement performance data and aggregate pavement routine maintenance cost data, both of which were available from records maintained by Indiana DOT. A brief outline of this concept is presented here.

The field performance curve of an in-service pavement is the result of combined action of traffic-loading, routine maintenance, and non-load-related factors such as climate and material ageing. The work of routine maintenance has the effect of recovering part of the pavement damages done by load and non-load related factors. A technique based on actual pavement performance curves was introduced to derive a zero-maintenance curve in order to estimate the total pavement damage that would have taken place without the presence of any maintenance work. This total damage was then separated into load and non-load related portion. The relative shares of these two factors formed the basis for allocating pavement routine maintenance and rehabilitation costs. The load-related costs were allocated on the basis of ESAL, and non-load related costs on the basis of VMT.

Georgia Highway Cost Allocation Study

The Georgia study of 1979 [8] was indirectly based on the Federal Highway Administration's 1964 study and used the incremental approach for highway cost allocation. This study considered the following 7 vehicle classes:

Cars
- Pickups, panels & other 2 axle single tire trucks
- 2 & 3 axle single unit trucks with dual rear tires
- 3 axle tractor truck semi-trailer
- 4 axle tractor truck semi-trailer
- 5 axle tractor truck semi-trailer
- Buses

Most of the data used, came from existing departmental files or was developed especially for this study. A FHWA publication, Highway Statistics 1976, was also a source of information.

The procedure of cost allocation in this study has three main steps.

The annual cost of construction and maintenance was developed. These annual costs were then allocated to vehicle types based on various allocation factors. 80% of surface maintenance costs were allocated based on axle miles of travel per vehicle type and the remaining 20% to trucks and buses alone based on VMT and 18kip axle equivalents per truck type and bus. 25% of resurfacing costs are allocated to all vehicles based on axle miles per travel and the remaining 75% to trucks and buses alone based on VMT and 18kip axle equivalents per truck type and bus. 85% of shoulder maintenance costs are allocated to all vehicles based on axle miles of travel per vehicle type and the remaining 15% is allocated to trucks and buses alone based on VMT and 18kip axle equivalents per truck type and bus. 100% of all other maintenance costs are allocated to vehicles based on VMT per vehicle type.

The annual contributions by vehicle type to Federal and State road user taxes that are dedicated to highways are calculated. The only road user tax in Georgia, which was dedicated to highways, was the 7.5-cent per gallon motor fuel tax. There were several Federal road user taxes though. According to the method, the annual contribution is allocated to all vehicles based on factors such as VMT and miles per gallon.

Finally, the annual costs and contributions are compared to find whether each vehicle type is paying its fair share of highway costs.

An update of Georgia Highway cost Allocation Study was conducted in 1981. [9] Two changes were incorporated in this update:

- The vehicle classes were changed. The 2 & 3 axle single unit truck with dual rear tires class was split into two individual classes of 2 and 3 axle single unit trucks with dual rear tires. Motorcycles and recreation vehicles were added to the Bus vehicle class.
- The road user tax in Georgia, which is dedicated to highways, in 1981 consisted of the 7.5 cent per gallon motor fuel tax, a second motor fuel tax consisting of 3% of retail sales price of motor fuel, and the interest accrued on the motor fuel taxes.

The study found that cars pay 80% of their responsibility while trucks pay only about 55% of their responsibility. Thus the study recommended the implementation of weight-distance tax.

Minnesota Highway Cost Allocation Study

This study, conducted in 1990 [10], was the first highway cost allocation study conducted in Minnesota. The FHCAS method was used. The procedure of cost allocation in this study had two main steps.

Forecasting all the factors required for cost allocation. The most important factor is VMT, which has been forecasted for year 1993 from year 1989 data. The VMT are forecasted for various classes of highway in Urban and Rural category individually. The revenues and expenditures were also forecasted for the year 1993. One difference form other state highway cost allocation studies is that the total revenue generated was considered for cost allocation in this study.

Allocating revenues and expenditures to various classes of vehicles. There were four types of vehicle taxes in Minnesota the time this study was performed. The fuel tax revenue was attributed to vehicle classes based on vehicle miles of travel on Minnesota highways and fuel economy for gasoline and diesel truck vehicles. The registration fees were attributed to vehicle classes using detailed breakdowns of collections by type of fee and registered weight provided by the Minnesota Department of Public Safety. The exercise taxes were attributed to vehicle classes using estimates of annual sales and prices. The fees for various types of driver license issued by Minnesota were attributed to vehicle classes in proportion to the number of Minnesota based vehicles. In order to allocate expenditures, both the Federal method and the Incremental method were considered, but the Federal Method was finally selected as a more widely used and more suitable method to allocate pavement maintenance cost, which forms a major portion of the expenditures.

Conclusions and Recommendations for HCAS in New Jersey

The primary objective of this study was to review methods for estimating infrastructure costs attributable to heavy vehicles. Relevant literature on federal and state cost allocation studies was reviewed. The results were presented above and are summarized next:

- Based on findings from the literature and discussions with state officials, it has been determined that a cost allocation study has not been performed for the state of New Jersey. Performing such a study would be highly recommended, since it helps develop a clear picture of the cost responsibility of each vehicle class and decide whether changes need to be made in order to charge each vehicle class its fair share of cost responsibility.

- In selecting the most appropriate method to be used for highway cost allocation in New Jersey, the trade-offs between data requirements, ease of use and update, and output detail need to be decided upon. The Arizona and Indiana approaches may provide useful guidelines in developing a relatively easy to use and update model. The advantages of such a model would be simplicity, minimum data requirements and availability of information through data collected for other programs. As a disadvantage, this approach will produce more aggregate results in terms of vehicle, highway and cost categories considered. The resulting level of accuracy will, in theory, be inferior to that of more detailed studies, such as the ones performed by Oregon, Georgia and Minnesota, which are based on FHCAS guidelines.

- A thorough consideration should be given to New Jersey specific conditions and requirements prior to developing any state highway cost allocation model. Whether a simplified or a more detailed approach is used, high levels of data accuracy and state specific conditions will help increase the accuracy of model results. In that sense, a simplified approach well tailored to New Jersey conditions is expected to produce more accurate results, compared to a more detailed, FHCAS like approach, based on default data.

The second objective of this study is to determine the availability of methods for estimating the impact of different types of buses on highway infrastructure, and the costs associated with these impacts. The above summarized, federal and state highway cost allocation studies treat buses as one vehicle class without any size and axle weight considerations for different types of buses. In some cases (Georgia) buses were even combined with other vehicle types (motorcycles and RVs) and considered within a common category. In other cases (Oregon) types of vehicles are not considered at all and the results are given based on registered gross vehicle weight distribution. The highway cost allocation studies do not consider different types of buses, thus their results cannot be used to address the second objective of this project.

The 1997 Federal HCAS estimated that the number of buses is 0.3% of the total number of vehicles and that buses account for 0.2% of total VMT. According to the Arizona model, the cost responsibility for buses on urban roads, allocated based on VMT, is 0.44% of the total costs. On rural roads, the cost responsibility for buses is allocated based on PCE, and accounts for the 0.53% of total costs. The Indiana study estimates the bus share of VMT to be 0.164% of total VMT and the bus share of cost responsibility to be 0.448% of total costs. Because of the small percentage of buses in the overall traffic and the associated small percentage of bus VMT, it can be concluded that the overall contribution of buses to highway pavement deterioration is negligible compared to trucks' contribution. These findings probably explain the lack of studies, which explicitly treat buses and estimate the impact of various types of buses to highway pavements.

As indicated by New Jersey Transit and City of Denver staff, buses very often may have a more prominent impact on pavements compared to trucks. This might very well be the case along bus routes with heavy bus traffic and frequent bus stops. This, together with the fact that several substantially different types of buses operate within each state, indicates that more attention should be given in the development of methods to estimate the impacts of various types of buses on highway infrastructure. The following section presents a review of methods that have been developed to estimate the impacts of various truck types on highways, and determine the applicability of these models to the estimation of bus impacts.

PAVEMENT DETERIORATION MODELS

Pavement maintenance or rehabilitation is generally carried out when the pavement reaches a pre-determined service level measure like PSI or PSR. These are measured from the extent of pavement rutting or cracking etc.

A typical pavement deterioration model incorporates three sub-models. [11]

1. Traffic Loading Simulation Model: This should model the heavy vehicle whose effect on pavement needs to be analyzed. There are several vehicle characteristics that affect pavement deterioration, including the following:
    a) Axle Load: The axle load affects all layers in a pavement structure and entails elastic, plastic and viscous deformations. [12] Pavement engineers generally use the concept of an equivalent single-axle load (ESAL) to measure the effects of axle loads on pavement. The AASHO Road Tests indicate that ESALs increase sharply (fourth-power relationship) with axle weight. The number of axles is also important: all other things being equal, a vehicle with more axles has less effect on pavements. [13]
    b) Type of tire: Tire is the component of the vehicle that comes into contact with the pavement. The type of tire treat, depth, etc. affects the pavement.
    c) Tire pressure: New types of radial tires can be used with higher pressure than before, and the wider single tires carry heavier loads (per tire) than dual tires. The total contact area between the tire and the pavement influences the damage caused by traffic. More contact between the tire and pavement i.e. lesser tire pressure results in less damage to the pavement. A study shows that the use of single tires results in a greater damage potential, relative to a similarly loaded dual-tired axle. [14]
    d) Suspension: The force acting on the road surface is very much acting as a dynamic load, which depends on:
        i. external static load
        ii. road roughness
        iii. suspension parameters of the heavy vehicles
        iv. vehicle speed

Information on suspension parameters is very difficult to gather. Several constants have been developed and are used instead, to account for the effect of suspension types. [12]

    e) Speed: In general, the pavement response decreases with increased vehicle speed.

All these factors must be considered in order to derive a comprehensive model of vehicle dynamics. One of the most well known models of this type is the Quarter car Model.

2. Analytical Models: These models should predict the deflection and stresses in the pavement under simulated wheel loading from the above model and must also consider the effect of environmental conditions in the area. The pavement factors that affect pavement deterioration are pavement structure, material, drainage and roughness. Climatic conditions that affect pavement deterioration are temperature, precipitation, frost heave and thermal cracking.

3. Transfer Function: This function relates the state of stress obtained from the analytical model to the pavement's overall performance. [11]

Types of Deterioration Models

Several deterioration models have been developed for flexible and rigid pavements over the years. A vast majority of these models are statistical adjustments to the original local conditions. Consequently they are not valid if the boundary conditions (i.e. temperature, materials and precipitation) are somewhat changed. There are five types of deterioration models: [12]

Statistical models: they need to be developed for individual boundary conditions as they rely on past data. Thus, in order to apply one that already exists, the boundary conditions must be identical.

Subjective models: they rely on present conditions and predict the future conditions probabilistically. The subjective models generally use Markov processes.

Empirical deterioration models: they are based on observations of deterioration on certain pavement sections. The deterioration is explained by using the boundary conditions in combination with the pavement structure, without using any models for explanation of what happens inside the pavement materials.

Mechanistic/Empirical Models: These models are easy to use and are divided into two parts:

- Mechanized Part: The material response under traffic loading is calculated by using mechanistic models that are often based on the theory of elasticity (despite the fact that this theory has imperfections). The Layer Elastic Analysis (LEA) is one such method that is often used in the industry. In Layer Elastic Analysis, the pavement structure is assumed to be composed of layers of material that are linearly elastic, homogeneous, isotropic, and infinite in horizontal extent. Loads are statically applied through circular footprints of uniform pressure and the stresses and strain in the pavement are calculated. Other frequently used mechanized methods include the Finite Element Method (FEM) and the Method of Equivalent Thickness (MET). In Finite Element Method, the structure is divided into a large number of smaller parts, or "elements." By breaking down the structure into elements, the pavement structural problem is transformed into a finite set of equations that can be solved using a computer. This method is particularly better at modelling rigid pavements. Method of Equivalent Thickness is a method to transfer a multi-layer system into a single-layer system, so that the pavement structure can be treated as one and the same material. MET is easy to use and can easily be programmed in a spreadsheet.
- Empirical Part: The calculated responses have to be linked to pavement distress in order to be useful. This is done via the empirical part of the model. The link between material response and pavement distress can be illustrated with the load equivalency factor (LEF). LEF and the concept of the equivalent single axle load, are developed from the AASHO Road Test.

Mechanized Models: These models exclude all empirical interference on the calculated pavement deterioration. They intend to calculate all responses and their effect on the pavement structure purely mechanistically. An example of a model like this is the Distinct Element Method (DEM) for granular materials. The model treats each granular particle individually. Forces and displacements are calculated for each particle and the total effect is the resultant of all individual particles. This method has a high demand of computer power when simulating large material samples with thousands or even millions of particles.

Examples of Pavement Deterioration Models

With the advancement in computer technology and the increase in computing power, it has become fairly easy to perform calculation intensive tasks on a desktop computer. Many new pavement deterioration models are available in software packages. Some of the deterioration models and software packages are reviewed in the following sub-sections to demonstrate how the above described concepts and methodologies work.

Mathematical Model of Pavement Performance (MMOPP)

The Mathematical Model of Pavement Performance (MMOPP) [12] has been developed by Ullidtz at the Technical University of Denmark. It is a mechanistic/empirical model that is mainly based on the method of equivalent thickness with Odemark transformations and Boussinesq equations for calculation of the pavement response. The program operates under Microsoft Windows.

The loads considered are dynamic and depend on:

- The present roughness of the roadway surface
- The wheel type
- The suspension system of the vehicle
- The mass and speed of the vehicle

The dynamic loads are calculated for short segments of road, for each vehicle, and for each time increment (season). The effects of the load in terms of reduction in asphalt modulus and increase in permanent deformation are determined. The effects of all loads during the season are then summarised and the new condition is used as input for the next time increment. Both climatic and environmental factors influence the performance of a pavement. In MMOPP the temperature of the asphalt layer and the effect of frost and thaw on the unbound materials and subgrade are considered.

MMOPP makes use of a simple mechanical analogue to load the pavement. The mechanical analogue consists of two systems, both of which include mass, spring and shock absorber. MMOPP calculates the strain at the bottom of the asphalt layer, which results in a reduction of asphalt modulus.

The main input parameters in MMOPP are pavement structure in terms of layer thickness and modulus for each layer and material properties such as plastic parameters, traffic that is simulated with different wheel loads defined by the user, and climate changes that are simulated with factors multiplied by the layer moduli.

MMOPP has been used to model 180 four-layer flexible pavement test sections of the AASHO Road Test [15] and performance tests in the Danish Road Testing Machine. [16]

Highway Design and Maintenance Standards Model (HDM IV)

The Highway Design and Maintenance Standards Model is empirical and it has been difficult to use it in countries with colder climates where phenomena such as frost heave and studded tires are common. The new version, HDM-IV,[12] has been supplemented with data in order to cover colder climates. At this stage the HDM-IV model is a β-version.

The input to the HDM-IV is extensive. It includes detailed information of both vehicles and pavements. The main input data includes:

- Pavement structure in terms of the structural number, which can be calculated from the layer thickness and moduli, drainage, and construction quality
- Traffic and vehicle fleet (defined as a number of vehicle types, vehicle load and number of axles/vehicle)
- Climate in terms of moisture classification and temperature classification

HDM-IV contains empirical deterioration models for most types of distresses that can be found on a road. The distresses calculated are: cracking, potholes, edge break, damaged and undamaged surface and rut depth. The empirical deterioration models in HDM-IV must be calibrated and validated for all local conditions at which the model is used.

PAVESIM

PAVESIM [17] was developed at The University of Iowa Public Policy Center. It is a computerised dynamic pavement deterioration model, which is applicable to Joint Concrete Pavements and considers various types of trucks.

Integrated into Pavesim are TruckSim and RigidPav. TruckSim was developed at the University of Michigan to model heavy vehicles. Using dynamic wheel loads from TruckSim, PaveSim simulates the performance of Joint Concrete pavements. RigidPav, a finite element program, performs a detail calculation of deflection and stresses in pavement.

PaveSim has four components: Road Rater, Pavement Consumption, Pavement Comparison and Pavement response. The consumption component has eight sub-modules. Default data is available for slab dimensions, concrete properties, dowel properties, subgrade modulus, axle load placement, and temperature distribution. The default data can be modified, if required, to better match local conditions. The Pavement Consumption component automatically calls TruckSim and accepts its output as input. In TruckSim, the class of truck to be analysed and its wheel or axle configuration needs to be chosen. Road profiles, axle load and speed are entered as inputs. The TruckSim output is stored in a text file and is input to the Pavement Consumption Module. The

Consumption component applies finite element analysis to determine the effective depth after a given number of passes of the truck.

As indicated in the literature, PaveSim is designed to calculate distress only for a particular kind of pavement and has been developed for trucks exclusively. Only by assuming that the characteristics of a particular type of bus are similar to the characteristics of one of the truck types modelled in TruckSim, PaveSim can be used to estimate pavement distress due to buses. This assumption however, may yield erroneous results.

FHWA and Pavement Deterioration Models

The FHWA initiated the Truck Pavement Interaction (TPI) research program in the mid 1980s. This program aimed at:

- Developing models of pavement's response and performance when subjected to the combined effect of load and environment
- Developing technologies and methodologies that help determine the damaging effect of climate only
- Studying the relationship between road profile and heavy vehicle dynamics

This research program is ongoing and information can be obtained from the program Webster. [18]

In summary, several applications have been developed to estimate the impact of various types of heavy vehicles on pavements. These applications have been developed specifically for trucks and consider vehicle characteristics such as axle load, type of tire, and tire pressure. The difference in vehicle characteristics between trucks and buses suggests that truck specific models should not be used in the analysis and evaluation of bus impacts on pavements. Even in cases in which the models are flexible enough to accept user specified inputs in terms of vehicle characteristics, the loading patterns of buses are not comparable to those of trucks and the suspension systems may vary considerably between trucks and buses.

BUS IMPACT RELATED STUDIES

All of the existing computerised pavement deterioration models have been developed explicitly for trucks. Extensive literature review indicates that very little attention has been given to the study of buses and very few studies deal with buses and their impact on pavements. After a thorough literature search and contacts with state DOTs and local authorities three documents were found to deal explicitly with the impact of buses on pavements. These documents include a published article [19] and a report on which this article is based, [20] which are the products of a study conducted at the California State University, and unpublished information on a study that was performed by the city of Denver. [21] Findings of these studies are reviewed in detail in the following sections.

Impact of Single Rear Axle Buses on Local Street Pavements

The work conducted at the California State University [19,20] has two primary objectives.

- To determine typical axle weights for different types of buses
- To evaluate the impacts of these buses on local street pavement sections

The first step estimated the axle loads for two types of buses. The buses that were considered in the analysis are the 30-foot Gillig Corporation transit bus and the 40-foot Flexible Corporation bus. Axle loads for fully loaded buses were provided by the manufacturers, while a Fortran program was devised to estimate the axle load for partially full or empty buses. The next step was to estimate ESALs using number of axles and axle loads. One-time single axle ESALs were calculated for minimum and maximum bus loading conditions, and 20 year ESALs were calculated assuming specific bus loading and headway criteria. The estimated values were then used to assess impacts of buses on various types of streets using three different approaches, namely the California design method, [22] a statistical method based on Pavement Maintenance System (PMS) data, and visual observation. The study focused only on the impacts of buses on flexible pavements.

The California design method was used to assess the cost of designing streets to accommodate buses by determining the actual axle loading that the pavement is subjected to by bus traffic. Statistical analysis was applied to PMS data to determine whether the pavement condition was significantly affected by transit usage. Visual observations were made in areas showing signs of obvious damage due to transit buses.

The study concluded that urban transit buses have an adverse impact on local street pavements. It was shown that there is statistically significant likelihood that fewer street segments with bus service have very good condition ratings as compared to segments without bus service. The impact of buses could be observed easily, particularly at bus stop locations. The study also concluded that to increase the structural sections to accommodate bus transit, the cost of arterials would be increased by less than five percent, while the cost of collectors would increase by fifty-eight percent.

To address the adverse impact of buses to pavements, two approaches were proposed. The first one recommends strengthening the structure of the roadways, especially collector streets that are used as bus routes. At bus stops structural pads could be provided to prevent premature failure of the pavement section. There are two problems associated with this approach. First, it will be costly to accommodate the weight of transit buses and local governments are already challenged financially. Second, strengthening the structure of streets used as bus routes will result in loss of flexibility in route scheduling, which is an advantage of bus over rail transit.

The second approach is to control the weight applied to the roadway pavement either by restricting the number of passengers or by adding a tag axle to the buses. The first solution is difficult to enforce and not economical from the transit agency's perspective, and the second solution would increase the cost of transit buses.

The County and City of Denver Study

A study to determine ESAL values for several different types of buses used in the city of Denver was performed for the regional Transportation District of Denver, Colorado. Information on bus manufacturer, model number and fleet description was collected for the 22 types of buses that were considered in the study. The buses varied in their axle spans, tire pressure and weights. Particular data that was gathered on each bus included gross vehicle weights, empty weights, number of axles, front, rear and tag axle weights, axle span and spacing and tire pressure as shown in Table 5.

ESAL factors were determined using three different methods. Results are shown in the last three columns of Table 5. ESALs in column 13 were determined based on gross vehicle weights and individual axle weights using a nomograph from the Asphalt Institute. ESAL factors for flexible and rigid pavements, shown in the last two columns of the table, were determined based on AASHTO Equivalency charts developed from the AASHTO Road Test. The methods used in this study consider traffic information such as an analysis period, annual average daily traffic (AADT), percent bus traffic and percent traffic growth, and pavement information such as subgrade strength, type of structural cross section and climate values, to estimate pavement specific ESAL factors for various types of buses. Using this information a comparative analysis of the relative impacts of different bus types to a particular type of pavement can be made.

TABLE 5 RTD Bus Fleet Information

Manufact. (1)	Model No. (2)	Subfleet Description (3)	(4) Gross Vehicle Weight (lbs.)	Empty Weight (lbs.) (5)	No. of Axles (6)	Front Axle Wt. (lbs.) (7)	Rear Axle Wt. (lbs) (8)	Tag Axle Wt. (lbs.) (9)	Axle Span (10) (Track)	Axle Spacing (11)	Tire Press, Frnt/Rear/Tag (psi) (12)	ESAL Factor A.I. (13)	ESAL Factor Flexible (14)	ESAL Factor Rigid (15)
Amtran/Int'l	Patriot - SFC 3706	101-155	27,080	14,000	2	10,020	17,060		96"	19'7"-20'3"	100/90	0.5	0.9	0.7
Amtran/Int'l	NC 3502	(6)	29,500	14,000	2	10,915	18,585		96"	19'7"-20'3"	100/90	0.7	1.1	1.1
Flexible	HD-31-35096	2301-2337	29,000	24,350	2	10,730	18,270		96"	19'11"	115/105	0.7	1.1	1.1
Flexible	40102-6T	7001-7045	39,500	31,000	2	14,615	24,885		102"	24'11"	115/105	2.6	3.5	3.8
GMC	T6H5307N	4801-4927	34,000	26,620	2	12,070	21,930		102"	23'9"	90/90	1.5	1.9	1.9
GMC	P8M4905A	1301-1312	34,000	25,480	3	12,000	17,000	5,000	96"	26'6"	105/80/70	0.7	0.9	0.8
Gillig	Phantom - M11	3001-3020	39,500	29,000	2	14,615	24,885		102"	23'3"	105/105	2.5	3.5	3.8
Gillig	Phantom -S50401	8001-8085	39,600	29,000	2	14,652	24,948		102"	23'3"	105/105	2.5	3.5	3.8
M.A.N.	SG310 (Articulated)	9001-9089	55,360	40,760	3	16,760	19,320	17,805	102"	18'7"/24'0"	115/105/115	3.8	2.4	2.4
MCI	MC7	1201-1209	36,000	26,500	3	12,000	19,000	5,000	80"/96"	23'9"	110/80/70	1.0	1.3	1.2
MCI	MC8	1401-1432	36,500	27,500	3	12,290	19,210	5,000	80"/96"	23'9"	110/80/70	1.1	1.3	1.3
MCI	102A3	1701-1721	40,000	27,250	3	12,500	22,500	5,000	86"/102"	23'9"	110/80/70	1.8	2.4	2.6
MCR	7000D	2507-2519	39,600	21,780	2	17,350	14,930		96"	19'9"	125/125	1.1	1.1	1.0
MCR	7000E Electric	2501-2506	46,200	32,020	2	21,410	21,110		96"	19'9"	155/155	3.3	3.2	3.3
MCR	7000D	2520-2526	39,600	21,460	2	16,830	15,130		102"	19'9"	125/125	1.0	1.0	1.0
Neoplan	N128 SuperSkyliner	1601	62,800	45,380	4	14,400	20,500	13,500	102"			4.2	2.1	2.2
Neoplan	AN-440	5001-5167	38,000	28,680	2	14,000	24,000		102"	22'5"	110/95	2.1	3.4	3.7
Neoplan	AN-440	CNG 5045-5049	38,000	28,680	2	14,000	24,000		102"	22'5"	110/95	2.1	3.4	3.7
Neoplan	AN-440	5201-5305	38,000	29,000	2	14,000	24,000		102"	22'5"	110/95	2.1	3.4	3.7
Neoplan	AN-340	1501-1528	44,000	34,600	3	14,000	19,620	10,290	102"	19'3.5"/4'4.5"	115/105/75	1.6	1.5	1.4
Neoplan	AN-340/3	1801-1820	49,200	39,000	3	15,755	21,480	11,500	102"	19'3.5"/4'4.5"	115/105/75	2.5	2.1	2.1
TMC	T80-206M (RTS)	6001-6005	39,600	28,000	2	14,652	24,948		102"	25'0"	110/100	1.8	3.5	3.8

(13) Based on axle weights, Gross Vehicle Weights and nomographic solution of EDLA (Ashalt Institute).

(14) Based on AASHTO Charts for flexible pavements, assuming a Pt of 2.5 and a SN of 5, and axle weights.

(15) Based on AASHTO Charts for rigid pavements, assuming a Pt of 2.5 and a slab thickness of 9 inches, and axle weights.

Source: Equivalent Single Axle Load Study, City and County of Denver, Colorado.

PROPOSED APPROACH AND DATA REQUIREMENTS

Based on the studies reviewed in the previous section, a method for estimating bus impacts on New Jersey highways is presented. A step-by-step discussion of the proposed method along with the data requirements associated with each step are discussed next, followed by an investigation on data availability from various sources in New Jersey.

Methodology

An outline of the proposed methodology is shown in the flow chart of Figure 3. Vehicle, pavement, traffic, and cost data requirements associated with this method are described next, followed by a detailed description of the methodology. Data items are listed according to the order in which the data requirement boxes are shown in the flow chart.

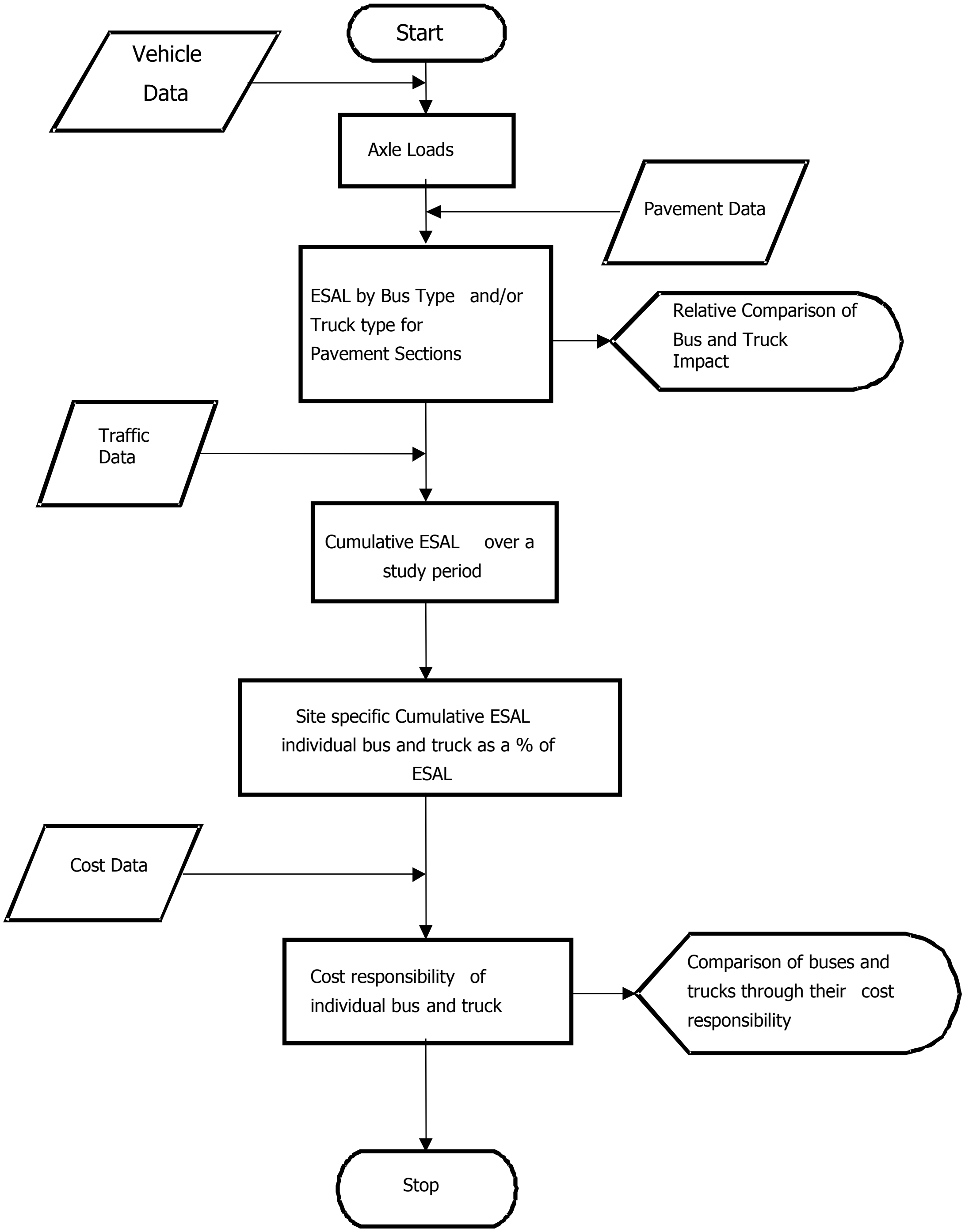


Figure 3 Proposed Methodology

Data Requirements

Vehicle Data

- Individual axle weights in a typical situation or when vehicle is fully loaded to capacity
- Number of axles for the vehicle.
- Distance between axles.
- Tire pressure.

For a more accurate calculation of axle loads (such as in the method used by the University of California researchers), the additional data required would be

- Length and width of the vehicle
- Seating and standing capacity
- Seating arrangement for a bus.
- Unladen weight of the vehicle
- Vehicle weight when fully loaded.
- Distance between front bumper and front axle.

It should be noted that axle configuration, distance between axles and number of tires per axle are parameters to be considered in estimating pavement damage attributable to heavy vehicles. Typical single, tandem and tridem axle configurations are shown in Figure 4.

Pavement Data

- Terminal Serviceability
- Type of pavement
- Design Structural Number (SN) for flexible pavement or Depth (D) for rigid pavememnt, if available.

If SN were not readily available then additional information would be required to calculate it as follows:

- Type of surface, base and subbase used.
- The layer coefficients of each layer
- Thickness of each layer
- Drainage coefficients for base and subbase.

Traffic Data

Traffic Data should be obtained for the routes used by the commercial vehicles considered in the study:

- Bus Schedule for peak and off peak periods on weekdays
- Bus Schedules for weekend
- Number of passes of a particular type of truck over a section of roadway
- Total ESAL for the current period.

Additional data requirements would include:

- Traffic growth rate if the analysis period is greater than one year.
- Bus or truck growth rate for the same period.

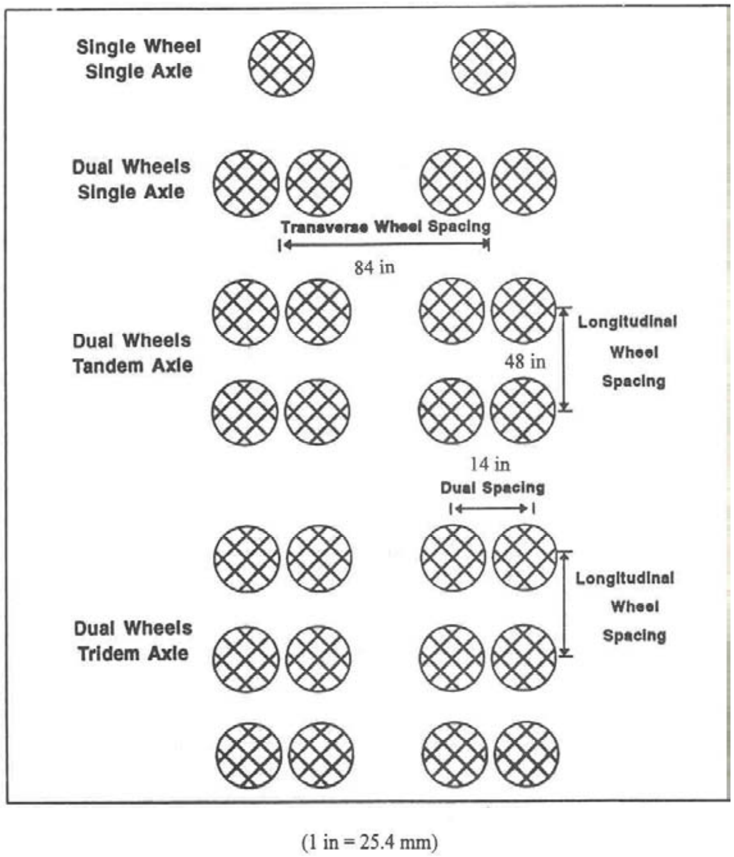
Cost Data

- The cost per volume of surface layer for each pavement type.

Additional data requirement would be as follows:

- Pavement maintenance cost over a certain time period.
- Pavement rehabilitation cost over a certain time period.
- The number of years in the time period considered.

The minimum data required would be referred to as “basic data” and the additional data required will be referred to as “extended data”.



Source: http://www.engg.ksu.edu

Figure 4 Heavy Vehicle Axle Configurations

A summary of these data requirements and their availability in New Jersey are as shown in Table 6.

Table 6 Data Availability in New Jersey

Data Requirements	Data Availability
Individual axle weights in a typical situation or when bus is fully loaded to capacity (crash load)	NJ Transit Bus Data
Number of axles for each vehicle	NJ Transit Bus Data
Distance between axles	NJ Transit Bus Data
Length and width of the vehicle	NJ Transit Bus Data * Axle span available instead of width
Seating and standing capacity	NJ Transit Bus Data
Seating arrangement for each bus	N/A Could be obtained from the manufacturer
Unladen weight of the vehicle	N/A Could be obtained from the manufacturer
Vehicle weight when fully loaded	NJ Transit Bus Data * Not readily available but can be computed from data obtained
Distance between front bumper and front axle	N/A Could be obtained from the manufacturer
Terminal Serviceability	Assumed as 2.5 or can be obtained from LTPP database
Type of pavement	HPMS database
Structural Number (SN)	HPMS database
Type of surface, base and subbase	N/A
Layer coefficients of each layer	N/A
Thickness of each layer	N/A
Drainage coefficients for base and subbase	N/A
Bus Schedule for peak and off peak periods on weekdays	N/A Could be obtained from NJTransit
Bus Schedules for weekend	N/A Could be obtained from NJTransit
Total ESAL for the current period	LTPP database
Traffic growth rate for the analysis period	NJDOT Webster *(1)* *Available online only for year 2000
Bus or truck growth rate for the analysis period	Can be obtained from NJ Transit for bus service
Pavement maintenance cost over a time period	LTPP database
Pavement rehabilitation cost over a time period	LTPP database
Number of years in the period considered	LTPP database
Cost per volume of pavement surface type	NJDOT

Samples of data available from HPMS database and LTPP database for New Jersey, relevant to the proposed methodology are shown in Tables 7 and 8 respectively.

Table 7 Sample of HPMS Database with Relevant Data for New Jersey

COUNTY_04	SECTION_ID_05	LRS_ID_10	BEG_MP_11	END_MP_12	PAVT_TYPE_50	SND_51
1	0M1017000410	01021017__00	0.41	0.83	4	3
1	P0 9 032130	00000009__00	32.13	32.5	4	6
1	P0 9 033190	00000009__00	33.19	33.31	6	6
1	P0 9 039640	00000009__00	39.64	39.89	6	6
1	P0 9 040220	00000009__00	40.22	40.4	4	5

Table 7 shows a sample of section identification codes and pavement characteristic data for a few New Jersey samples available in HPMS database. The COUNTY_4 column represents the FIPS county code for New Jersey. The SECTION_ID_05 column represents a 12 character county wide unique identifier for New Jersey. The LRS_ID_10 column along with BEG_MP_11 and END_MP_12 column permits users to reference HPMS information to map locations of road sections. The above three columns were used to develop a GIS map as shown in Figure 5. The PAVT_TYPE_50 column gives information on the type of pavement surface used in that sample section of roadway. The SND_51 column provides the Structural Number (SN) for flexible pavement or Depth (D) for rigid pavements. The data available in PAVT_TYPE_50 and SND_51 columns are required as inputs for Pavement Data in the proposed methodology. Detailed information on these columns and their values can be obtained from the HPMS Field Manual. [24]

Table 8 Sample of LTPP Database with Relevant Data for New Jersey

SHRP_ID	STATE_CODE	CONSTRUCTION_NO	IMP_DATE	IMP_COST
0502	34	2	8/19/1992	25
0503	34	2	8/13/1992	63
0504	34	2	8/21/1992	64
0505	34	2	8/21/1992	25
0506	34	2	8/20/1992	25

Table 8 shows a sample of section identification code, pavement maintenance or improvement records and cost associated with pavement improvement or maintenance. This data is available in the LTPP database and was accessed using the DataPave 2.0 [25] program developed by Federal Highway Administration. The SHRP_ID column provides the test section identification number assigned by LTPP program. STATE_CODE column represents the FIPS state code. The SHRP_ID combined with STATE_CODE provides a unique identification in LTPP database. The

CONSTRUCTION_NO column shows the number of times the pavement section has undergone changes from the time it was accepted into the LTPP program. The IMP_DATE column shows the date on which the major improvement was performed. If the date of pavement improvement performed before or after the date available in IMP_DATE can be obtained for a pavement section considered, then the number of years between two successive pavement improvements can be calculated. This would be one of the cost data inputs required in the proposed methodology. The IMP_COST column shows the Cost in thousand dollars per lane mile for the improvement performed. This is an other cost data input required in the proposed methodology.

Procedure

Based on the literature findings presented so far in this report, ESAL is often the parameter used to allocate load-related costs. Thus, estimating ESALs for different types of buses is a very important first step in determining cost responsibility for these types of vehicles. The steps of the proposed method are as follows:

Step 1

The first step in this methodology is the calculation of axle loads. “Basic data” from the vehicle data requirements, which is typically available from the vehicle manufacturer, is used to determine the axle loads for the different axles of the vehicle. Axle load data are usually given for crash load conditions, which represent fully loaded buses. If “extended data” are available, axle loads may be estimated for different vehicle loadings using a model such as the one developed in [20]. Alternatively, an average passenger weight (for example 150 lbs.) may be considered and an assumption may be made that the decrease in axle load due to less-than-crash-load conditions is equally distributed among the vehicle axles, or it is distributed proportionally to the crash load sustained by each axle. Following this procedure, axle loads for different types of buses and different loading conditions may be estimated. Similar information may be obtained for various truck types.

An example application of this procedure for various types of buses operated by NJ Transit is shown in Table 9. In this example, it was assumed that pavement terminal serviceability index is 2.5 and Structural Number is 5, values similar to those used in the city of Denver study. This analysis, as well as the analyses shown in the following sections, was done assuming flexible pavement, since this type of pavement represents almost 80 % of pavement surface in New Jersey. Data provided by New Jersey Transit is shown in the first rows of the table. These data include vehicle design characteristics and axle weight. The axle weight is given for typical values, shown as Weight Represented in the table. For example, typical load for the two commuter buses is the seated load, while for the other types of buses is the standing load. ESALs for each axle and for the whole vehicle for the typical load and for crash load are shown in the bottom part of the table. The ESAL of a vehicle is affected by the pavement type. ESALs can also be calculated by multiplying the axle load and the LEF specified in the AASHTO tables. LEFs are available for bitumen and concrete pavements. But they are not specified for Composite pavements and hence must be assumed from experience.

To estimate ESALs for crash load, an average weight per passenger of 150 lbs. was assumed. An additional weight equal to the difference between the number of passengers under typical and crash conditions multiplied by the average passenger weight was then added in the vehicle weight, and distributed evenly among the vehicle axles.

Step 2

Information on pavement design characteristics and materials properties is used to estimate ESALs by vehicle type. Depending on data availability, a simplified method, such as the one described in [20] or a more detailed one, such as the AASHTO procedure described in the Appendix, may be used.

Table 9 NJ Transit Bus Data and ESAL Estimation

Bus Type	**Commuter**	**Commuter**	**Transit Artic.**	**Suburban Artic.**	**Transit**	**Transit**
Overall Length (ft)	40	45	60	60	40	40
Number of Doorways	1	1	3	2	2	2
Model No	MCI 102D3	MCI 102DL3	Volvo Type A	Volvo Type B	Flexible Metro D	Nova A
Number of Axles	3	3	3	3	2	2
Front Axle Weight (lb.)	13580	14800	14800	14900	11265	14480
Rear Axle Weight (lb.)	19540	22040	22400	22400	22375	22360
Tag Axle Weight (lb.)	9340	11060	15700	15900	n/a	n/a
Front-Rear Axle Spacing (in)	279	318	216	216	299	299
Rear-Tag Axle Spacing (in)	48	48	291	291	n/a	n/a
Axle Span (in)	86	86	86	86	85	86
Tire Pressure (psi)	110	110	110	110	110	110
Number of Front Axle Tires	2	2	2	2	2	2
Number of Rear Axle Tires	4	4	4	4	4	4
Number of Tag Axle Tires	2	2	2	2	n/a	n/a
Weights Represent	seated load	seated load	standing load	standing load	standing load	standing load
seated load	49	57	66	65	45	47
nominal standing load	72	79	99	98	64	70
Crush Load	75	83	116	115	75	77
ESALs[*]	**Typical bus load**					
Front Axle	0.32	0.45	0.45	0.46	0.14	0.41
Rear Axle	1.38	2.20	2.33	2.33	2.33	2.32
Tag Axle	0.06	0.13	0.57	0.61	-	-
Total bus ESAL	1.76	2.78	3.36	3.41	2.47	2.73
ESALs[**]	**Crash load**					
Front Axle	0.46	0.64	0.85	0.87	0.24	0.62
Rear Axle	1.77	2.73	3.48	3.48	2.97	2.96
Tag Axle	0.11	0.21	1.04	1.09	-	-
Total Bus ESAL	2.35	3.58	5.38	5.44	3.22	3.58

Information on pavement condition may be obtained through the Highway Performance Monitoring System (HMPS). HPMS includes limited data on all public roads, more detailed data for a sample of the arterial and collector functional systems, and area-wide summary information for urbanized, small urban, and rural areas. A major purpose of the HPMS is to provide data that reflects the extent, condition, performance, use, and operating characteristics of the Nation's highways. Some of the data relevant for our study that can be accessed through a GIS application by just pointing and clicking on a street in the map shown in Figure 5 are Type of pavement, Structural Number (SN), Traffic data etc.

The sum of individual axle ESALs estimated using these methods provides the ESAL for the whole vehicle and for one pass of this vehicle over the pavement considered in the analysis.

Vehicle ESAL estimates for the NJ Transit vehicles are shown for Typical Bus Loads and Crush Loads in Table 9. Discussion with staff from NJDOT and NJ Transit brought to focus that the ESAL values for busses with Typical Bus Loads represented a more reasonable value of ESAL.

Outcome 1

At this point, a comparative analysis may be performed on the relative impact of different types of buses (and/or trucks). The ESALs available for different vehicles provide us with a comparison of the relative damage that the vehicles cause due to a single passage over the pavement. Although this information is not adequate to estimate cost responsibilities for different types of vehicles it provides useful insights on which type of bus has a more prominent negative impact on a particular type of pavement.

Results of the NJ Transit example shown in Table 9 indicate that the Volvo type A and B buses are expected to cause more damage on the pavement considered in the analysis, compared to the other types of buses operated by NJ Transit.

Step 3

ESALs estimated so far are representative of a single pass of a vehicle over the pavement. Traffic data are required to determine the cumulative ESALs over an analysis period. For buses, the number of passes over the analysis period may be calculated from the weekly transit schedule. Based on information on bus peak/off-peak and weekday/weekend scheduling and bus type operating on each route, the number of vehicle passes over a particular roadway section for a typical week may be estimated. These values can be extrapolated to obtain annual number of passes. For a multi-year estimate, a traffic growth factor should be considered in the analysis. The number of passes obtained for each vehicle type is then multiplied with its ESAL and the results are summed together to obtain the annual ESAL for a particular roadway segment. For trucks, the annual number of passes and subsequently ESALs may be obtained directly from classification counts. Figure 6 shows the WIM (weight-in-motion) locations in New Jersey where classification counts are taken.

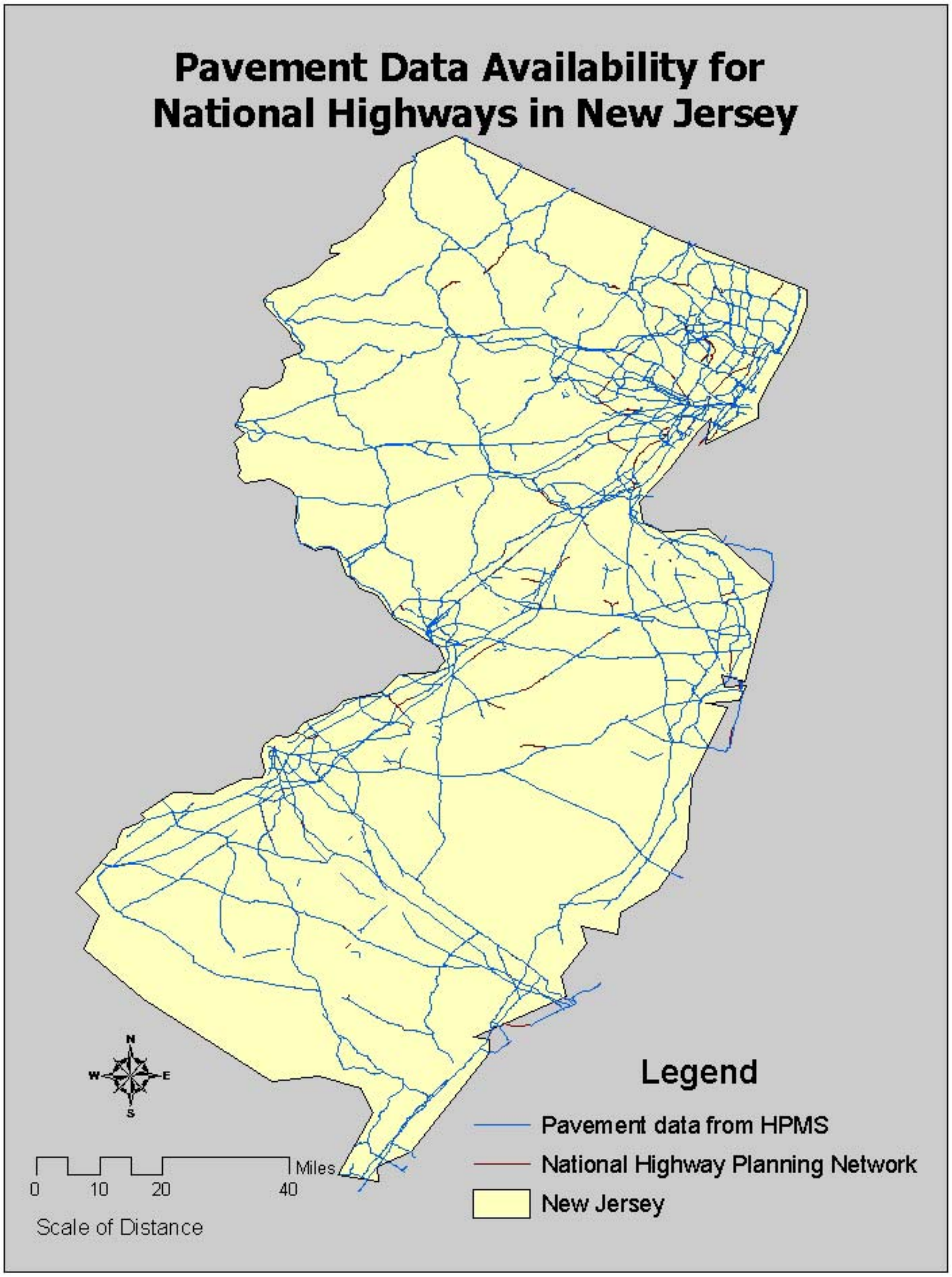
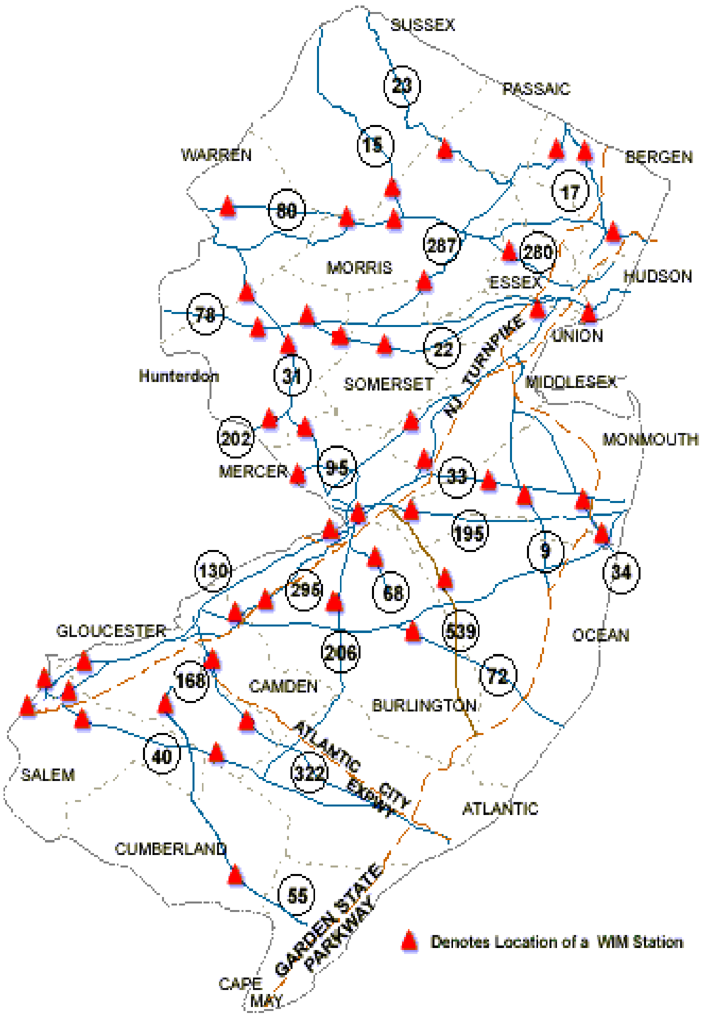


Figure 5 New Jersey Pavement Data Availability



Source: http://www.state.nj.us/transportation/count/vclass/class_2001.html

Figure 6 WIM Station Locations in New Jersey Vehicle

Step 4
The ESAL for any type of bus or truck at a particular site may be estimated as a percentage of total ESALs at that site. In a simplified approach, load related infrastructure expenditures may be allocated to different types of vehicles based on their cumulative ESALs as it will be described in the next section.

Alternatively, cost increments due to the vehicle's usage of the pavement may be determined following the method used in the California study. In that study, the California Design Method, based on cohesion and frictional properties, was used to determine the required thickness of poor subgrade and good subgrade asphalt concrete pavement for arterials and collectors separately, without considering any bus service on them. Then the cost per linear foot of the structural section was determined by assuming a cost of aggregate and asphalt concrete per cubic foot. The same procedure was followed for determining the cost of collectors and arterials considering the effect of buses on them. The results could then be compared to determine the increase in pavement cost due to buses using these arterials and collectors.

Another alternative considers a hypothetical pavement section, such as the one shown in Figure 7. The hypothetical highway pavement section chosen is a 3-layered pavement section, with an asphalt layer, a non-stabilized base layer and a subbase layer on a subgrade. Thicknesses of the aggregate layers were chosen arbitrarily, however, they do represent some typical pavement sections in New Jersey.
This pavement was analysed for the number of Equivalent Single Axle Loads (ESAL's) that can be applied to the pavement system before: (1) the pavement system's serviceability, which is based on the system's ability to serve the public in an acceptable manner, falls below a level that is acceptable, and (2) the system's true mechanisms of failure, in this case fatigue cracking and rutting, occurs. For this purpose two types of procedures were followed:

- Procedure (1) is based on the 1993 AASHTO Pavement Design Procedure, which is an empirical design method.
- Procedure (2) is based on linear-elastic theory and regression equations developed from field analysis, which is termed empirical-mechanistic.

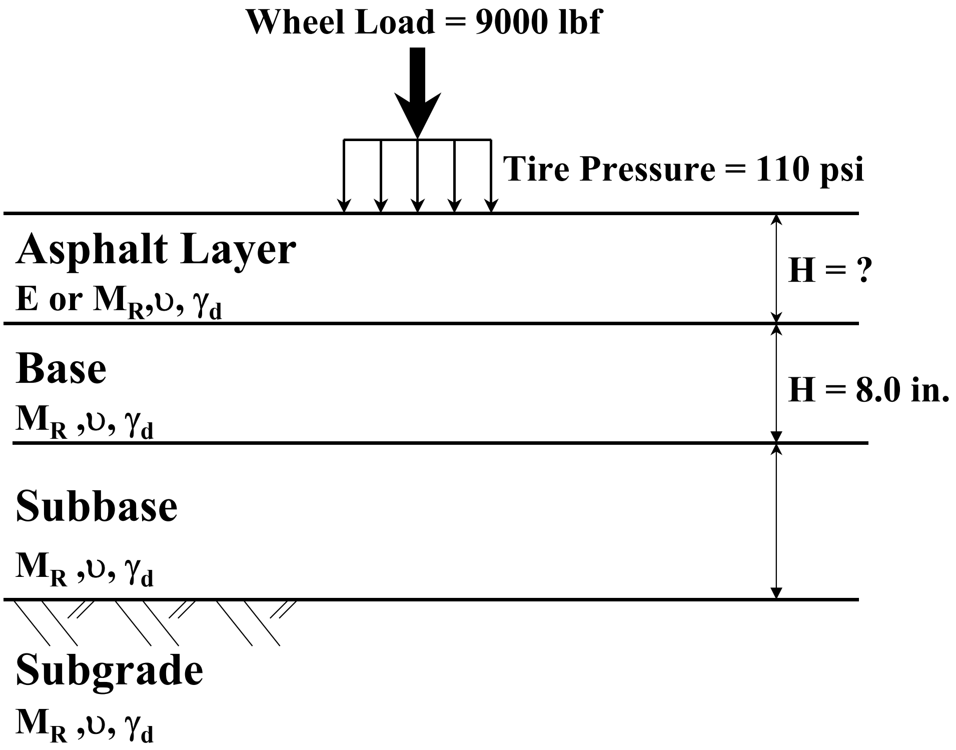


Figure 7 Pavement Section Used for Comparative Analysis

AASHTO Empirical Procedure

The AASHTO procedure is based on the results from the AASHO Road Test that was conducted in 1957. Modifications to the procedure have occurred since its inception to the version currently used. The procedure is based on determining a structural number (SN) of the pavement section that is based on the contributions of each of the pavement system's layers. The main parameters of each layer used consist of the layer's thickness, the layer coefficients and the drainage characteristics of the layer. As an example, Table 10 shows the "typical" parameters used in New Jersey. These parameters are also recommended as default parameters if information on the pavement system is unknown.

Table 10 Structural Number Inputs

Material	Layer Coefficient (a_i)	Drainage Coefficient (m)
Asphalt Layer (a_1)	0.44	N.A.
Base Layer (a_2)	0.14	1.0
Subbase Layer (a_3)	0.11	1.0

The layer coefficient (a_i) is a parameter that was statistically derived at the AASHO road test. The base layer coefficient and the subbase layer coefficient are assumed to have the typical values for New Jersey and remain the same throughout this analysis. But the asphalt layer coefficient is varied. Layer coefficient is a parameter that is based on the resilient modulus of the material. This parameter is a stress dependent parameter and for asphalt layer, also highly temperature dependent. Work conducted by Van Til et al. (1972) provided a guideline to convert the resilient modulus of asphalt, determined at 70^{o}F, to a structural coefficient that can be used in the AASHTO design procedure. Figure 8 is based on this work, with the resilient modulus portion greater than 500,000 psi extrapolated for the determination of the structural coefficient of the asphalt layer for the different traffic speeds.

Therefore, for the asphalt layer, the resilient modulus was chosen to be evaluated at one temperature (70^{o}F), however, it would be analyzed over different traffic loadings; (1) Stop-and-Go (less than 4 mph), (2) Slow (approximately 15 mph), and (3) Normal Conditions (approximately 60 mph). Typical asphalt resilient modulus values of each of these speeds are shown as Table 11. Also shown in the table is the resilient modulus value used in the AASHO Road Test, which was also used in the analysis.

Table 11 Resilient Modulus Values of the Asphalt Layer Based on Traffic Speed

Traffic Speed (mph)	Resilient Modulus (psi)
< 4 mph	300,000 psi
approximately 15 mph	500,000 psi
approximately 60 mph	700,000 psi
AASHO Road Test	450,000 psi

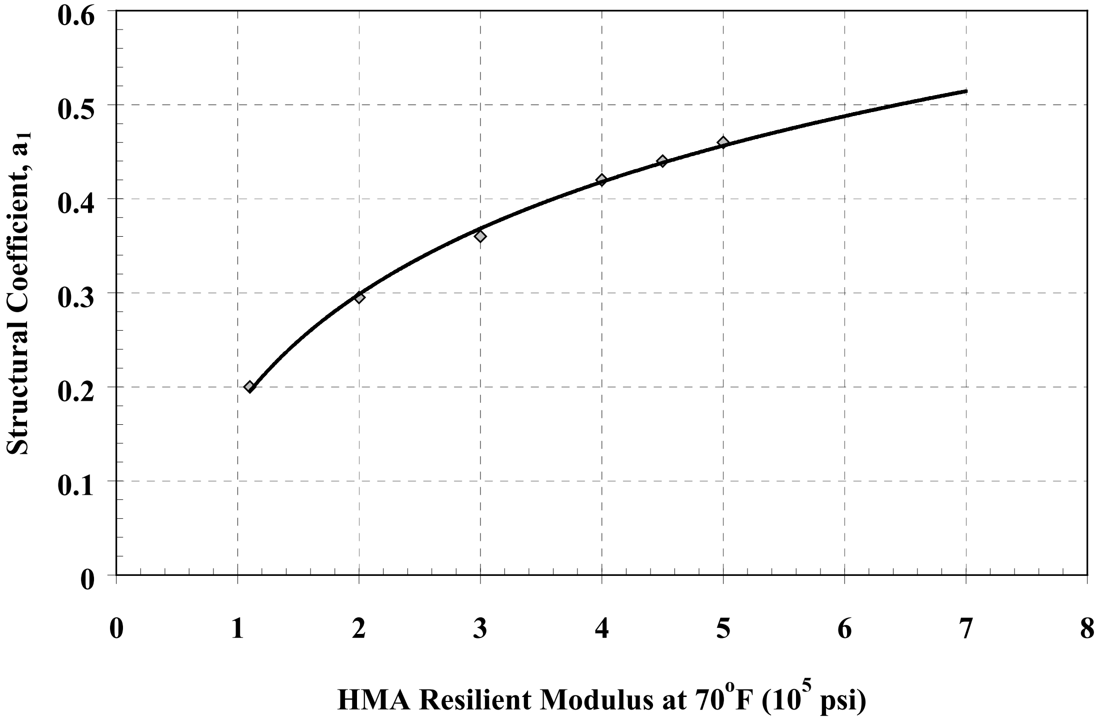


Figure 8 Structural Coefficient Determination from Hot Mix Asphalt (HMA) Resilient Modulus

A regression equation of the points was determined to provide a simple input equation to determine the structural coefficient (equation (1)). This equation was used for the determination of the structural coefficients for the AASHTO design procedure.

$$a_1 = 0.1723(\ln(M_R)) + 0.179 \qquad R^2 = 0.998 \qquad (1)$$

A sensitivity analysis was conducted, utilizing the hypothetical pavement section, with the AASHTO DARWIN computer program. The program is based on the design procedure and allows to easily vary parameters to evaluate the pavement system's sensitivity to these parameters. The program design criteria were set to determine the number of design ESAL's based on the pavement section chosen for a design life of 20 years. For the analysis, only the asphalt section properties varied, with the base, subbase, and subgrade properties remaining constant. Other variables used in the analysis are shown for Highways in Table 12 under “Highway”. Alternatively, if the analysis pertained to local roads, the values listed under “Local Roads” could be used. These parameters are default parameters provided in the computer program, except for the effective subgrade resilient modulus. Therefore, the sensitivity analysis is based on varying the asphalt thickness and the asphalt resilient modulus, which is a function of the traffic speed and pavement temperature of 70^0 F. Results of the analysis are shown as figures 9 through 12. The regression equations shown in the figures represent how the ESAL’s relate to the needed thickness of the asphalt layer. Therefore, once the design ESAL’s are known, the necessary asphalt layer thickness can be computed for the pavement section profile shown in Figure 7. As expected, as the resilient modulus of the asphalt increases (or traffic speed increases) so does the design ESAL’s for the same asphalt thickness.

Table 12 AASHO ESAL Design Input Parameters

Input Parameter	**Used (Recommended) Value**	
	Highway	Local Roads
Initial Serviceability	4.2	4.2
Terminal Serviceability	2.5	2.0
Reliability	95 %	90%
Standard Deviation	0.47	0.33 (Rigid) 0.44 (Flexible)
Effective Subgrade Resilient Modulus	4,500 psi	4,500 psi

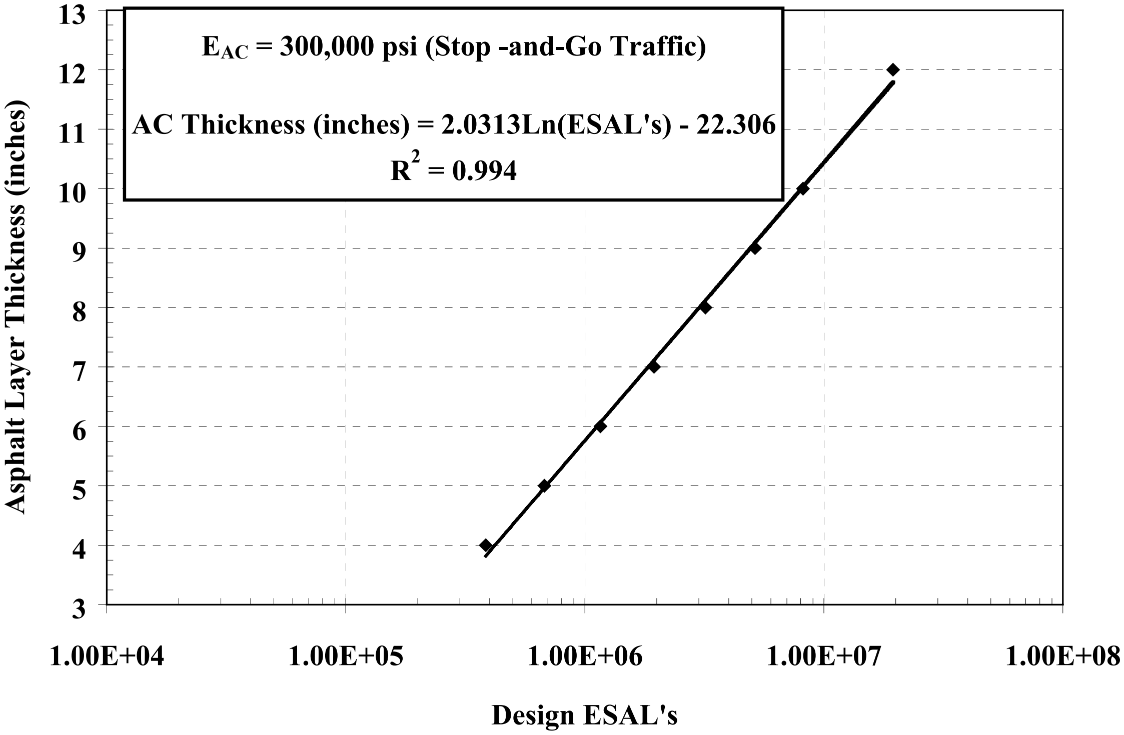


Figure 9 Design ESAL’s vs. Asphalt Layer Thickness for Stop-and Go Traffic Speeds for AASHTO Empirical Procedure

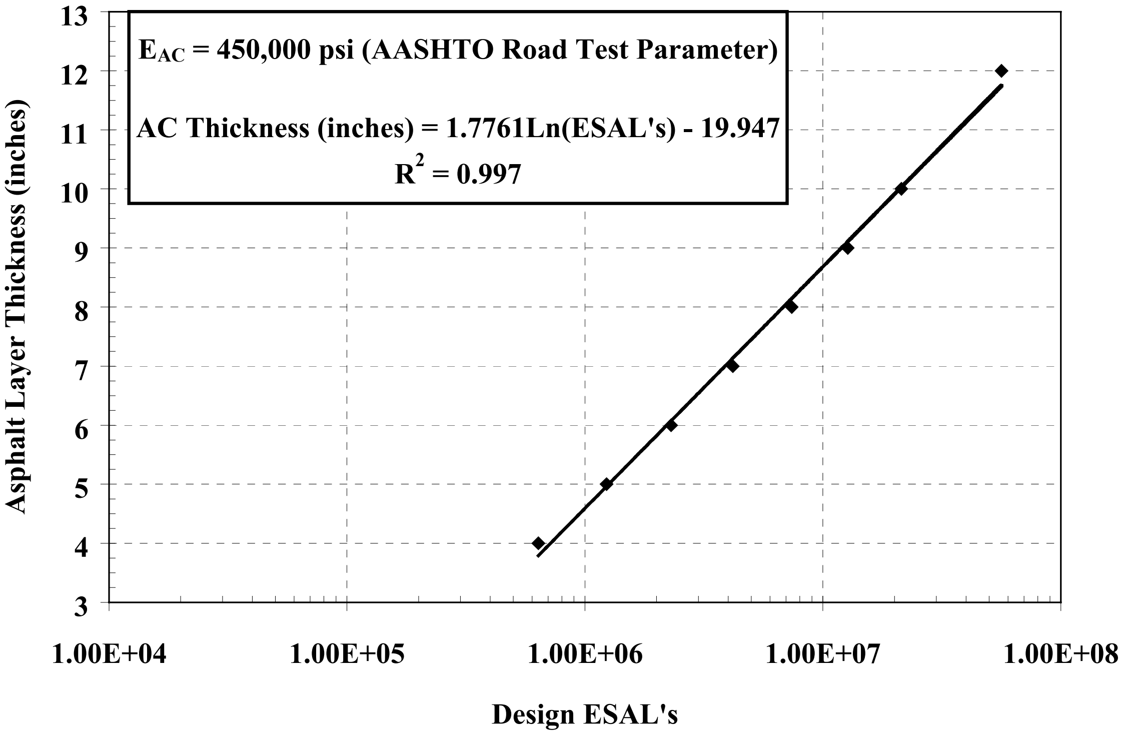


Figure 10 Design ESAL’s vs. Asphalt Layer Thickness Using the AASHO Road Test Parameters for AASHTO Empirical Procedure

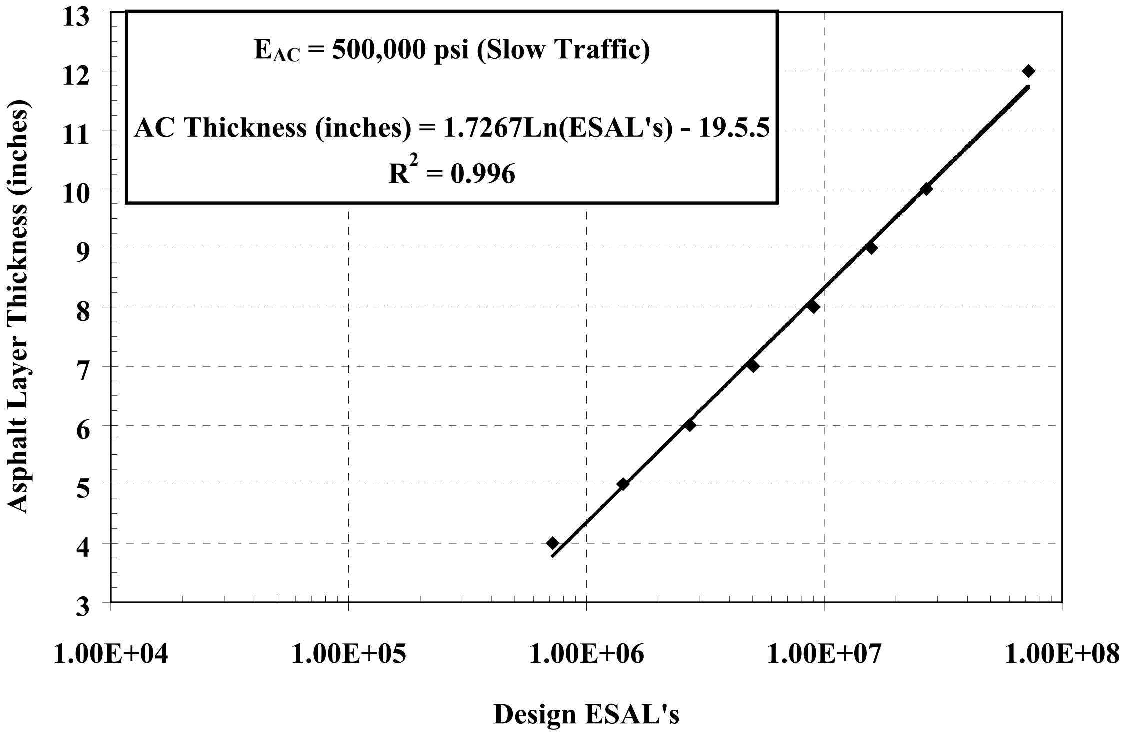


Figure 11 Design ESAL’s vs. Asphalt Layer Thickness for Slow Traffic Speeds for AASHTO Empirical Procedure

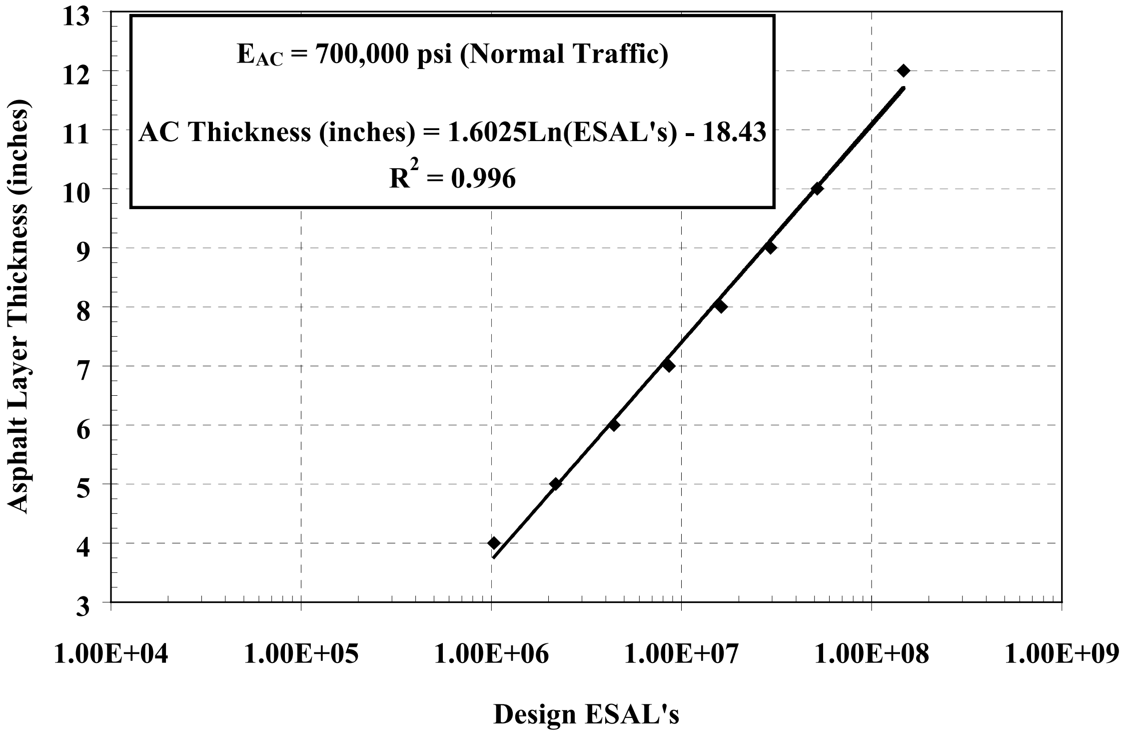


Figure 12 Design ESAL’s vs. Asphalt Layer Thickness for Normal Traffic Speeds for AASHTO Empirical Procedure

Empirical-Mechanistic Approach

To accompany the AASHTO design approach, an empirical-mechanistic approach was also evaluated utilizing the same pavement section and same resilient modulus parameters shown in Figure 7. However, for the mechanistic approach, since it is based on elastic layer theory, values of Poisson's ratio were needed for each of the layers. These parameters were assumed based on Table 13.

Table 13 Poisson Ratios for Different Materials

Material	Range of Values	Typical Value
Hot Mix Asphalt	0.30 - 0.40	0.35
Portland Cement Concrete	0.15 - 0.20	0.15
Untreated Granular Materials	0.30 - 0.40	0.35
Cement-Treated Granular Materials	0.10 - 0.20	0.15
Cement-Treated Fine-Grained Soils	0.15 - 0.35	0.25
Lime-Stabilized Materials	0.10 - 0.25	0.20
Lime-Fly Ash Mixtures	0.10 - 0.15	0.15
Loose Sand or Silty Sand	0.20 - 0.40	0.30
Dense Sand	0.30 - 0.45	0.35
Fine-Grained Soils	0.30 - 0.50	0.40
Saturated Soft Clays	0.40 - 0.50	0.45

The analysis was conducted with the elastic layer program developed by the Washington State DOT called EVERSTRESS. The loading conditions used represent typical tire inflation pressures (110 psi) and also model the 18-kip axle load of the ESAL (9,000 lb wheel load).

For the mechanistic evaluation, the elastic layer program was used to determine strains at two different locations within the pavement section. The tensile strain was determined at the base of the asphalt layer. This strain causes fatigue cracking in the asphalt. The compressive strain was also determined at the top of the subgrade layer. This strain causes rutting within the pavement section. Using these two strain components with equations developed by the Asphalt Institute, the number of loading repetition until failure can be determined for both fatigue cracking and rutting. Figures 13 through 16 show the number of loading repetitions (can also be called design ESAL's) until rutting failure occurs, while Figures 17 through 20 show the number of loading repetition until fatigue cracking failure occurs. Again, like in the AASHTO procedure, once the user determines the design ESAL's from a particular traffic scheme, it can be inserted into the regression equations to determine the asphalt thickness needed.

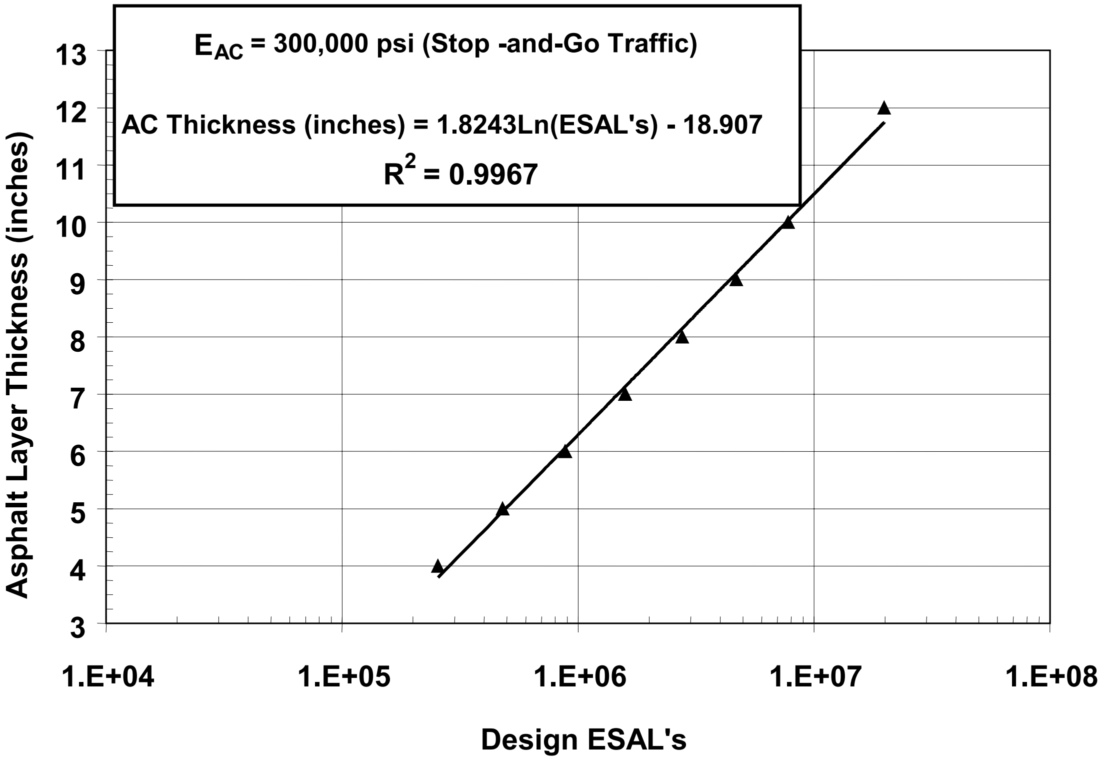


Figure 13 Number of Loading Repetitions (Design ESAL’s) Until Rutting Failure for Stop-and-Go Traffic Speeds for Empirical-Mechanistic Approach

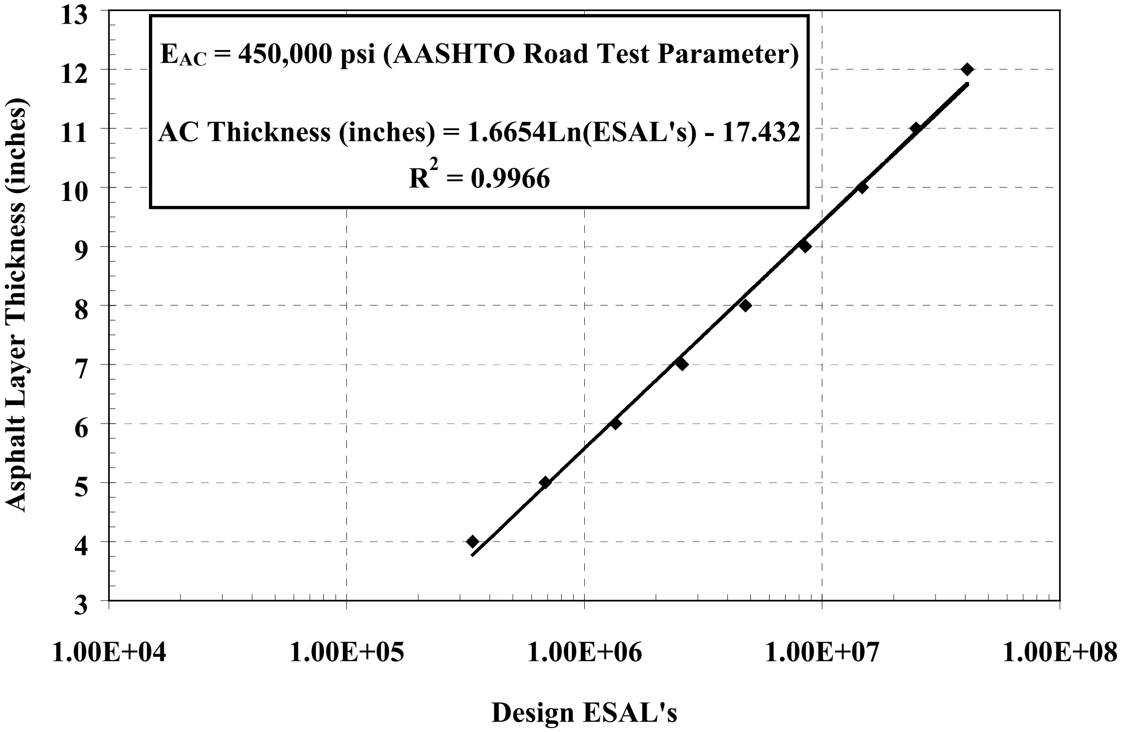


Figure 14 Number of Loading Repetitions (Design ESAL's) Until Rutting Failure for AASHTO Road Test Parameters for Empirical-Mechanistic Approach

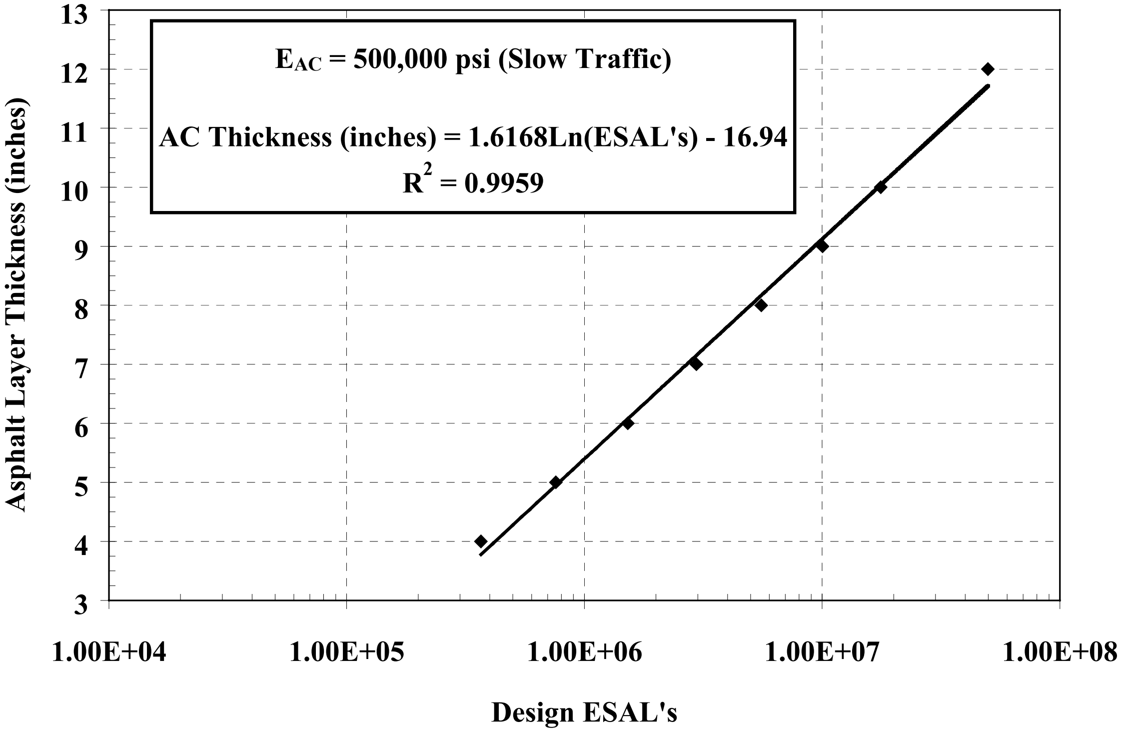


Figure 15 Number of Loading Repetitions (Design ESAL's) Until Rutting Failure for Slow Traffic Speeds for Empirical-Mechanistic Approach

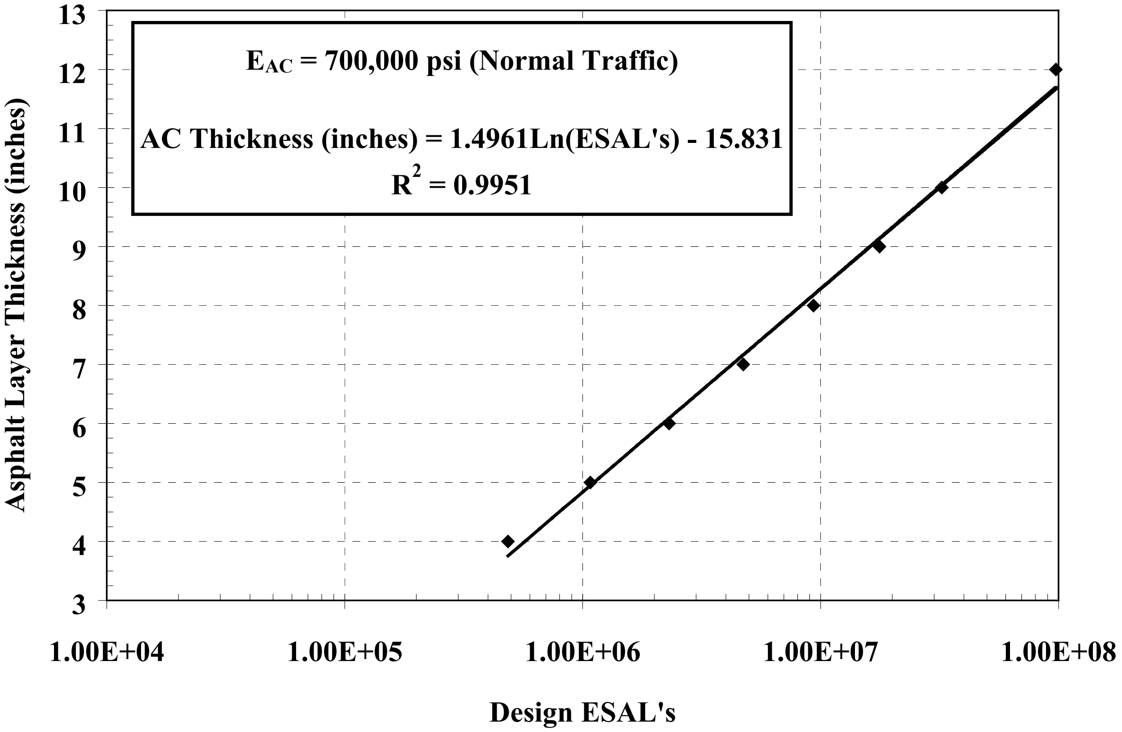


Figure 16 Number of Loading Repetitions (Design ESAL's) Until Rutting Failure for Normal Traffic Speeds for Empirical-Mechanistic Approach

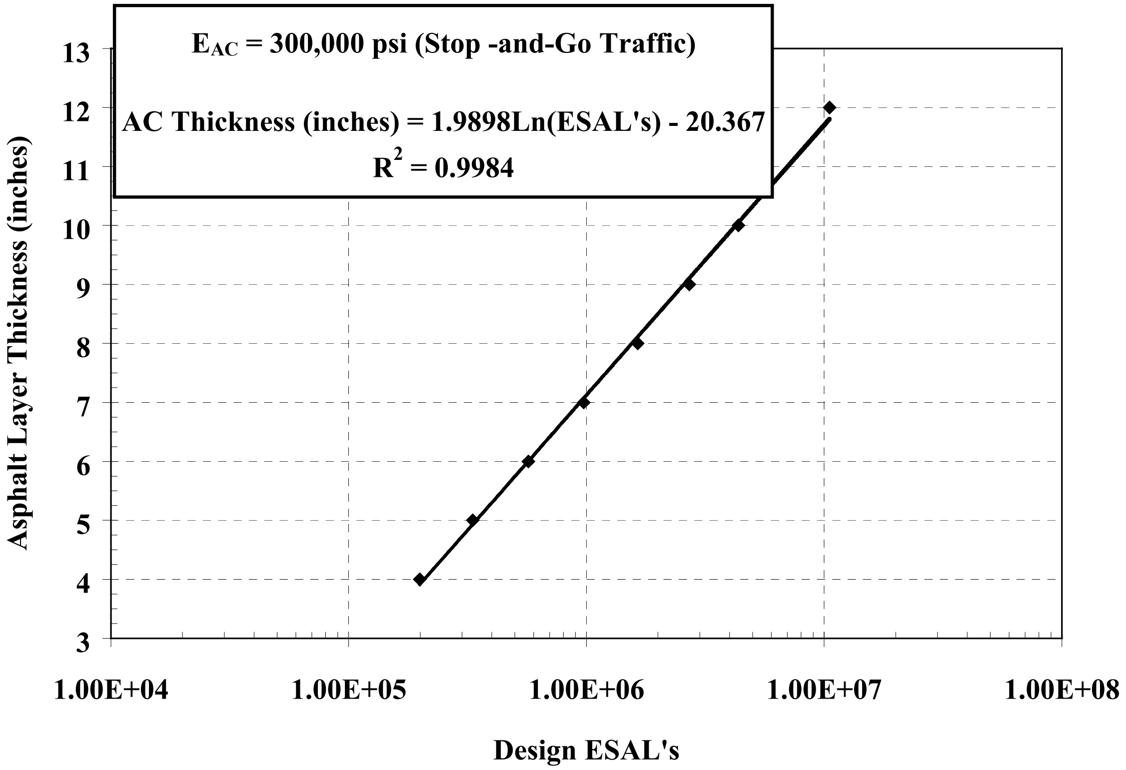


Figure 17 Number of Loading Repetitions (Design ESAL's) Until Fatigue Cracking Failure for Slow Traffic Speeds for Empirical-Mechanistic Approach

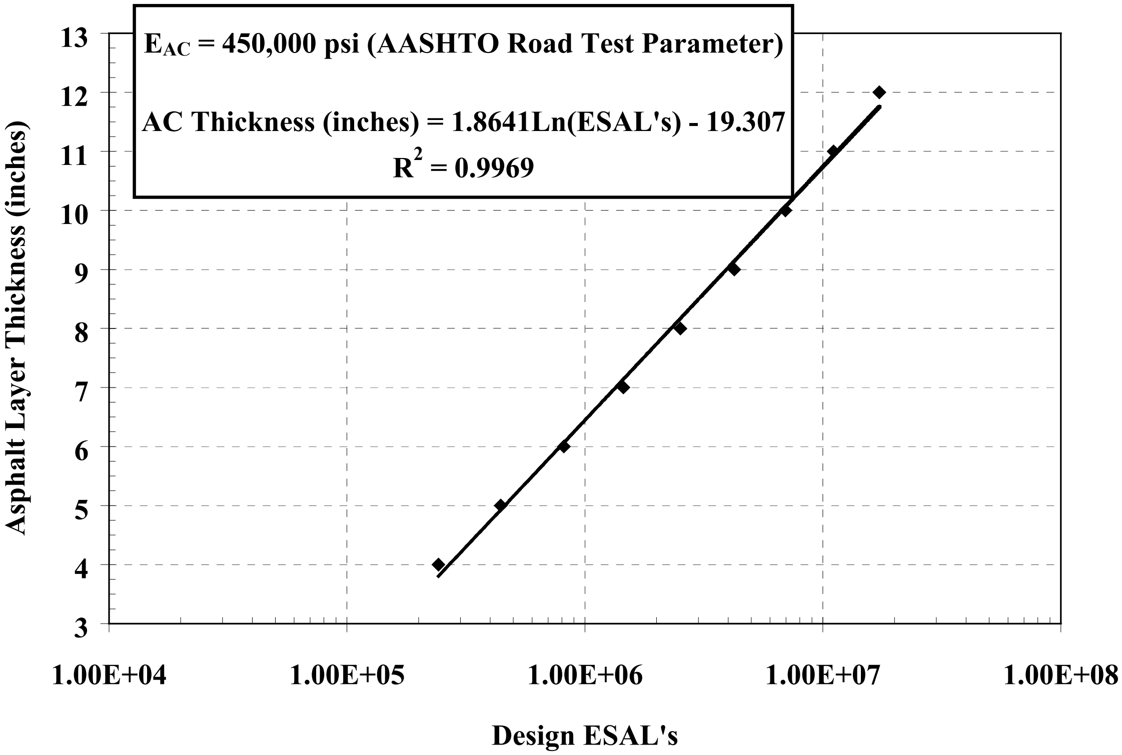


Figure 18 Number of Loading Repetitions (Design ESAL's) Until Fatigue Cracking Failure for AASHTO Road Test Parameters for Empirical-Mechanistic Approach

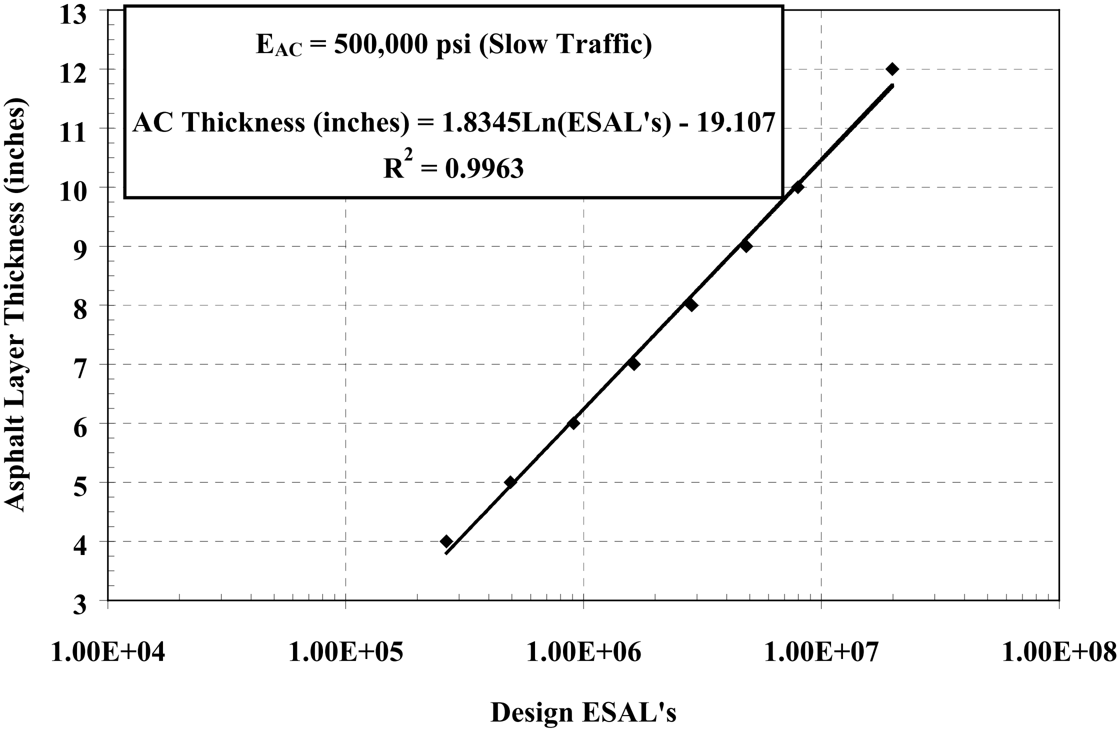


Figure 19 Number of Loading Repetitions (Design ESAL's) Until Fatigue Cracking Failure for Slow Traffic Speeds for Empirical-Mechanistic Approach

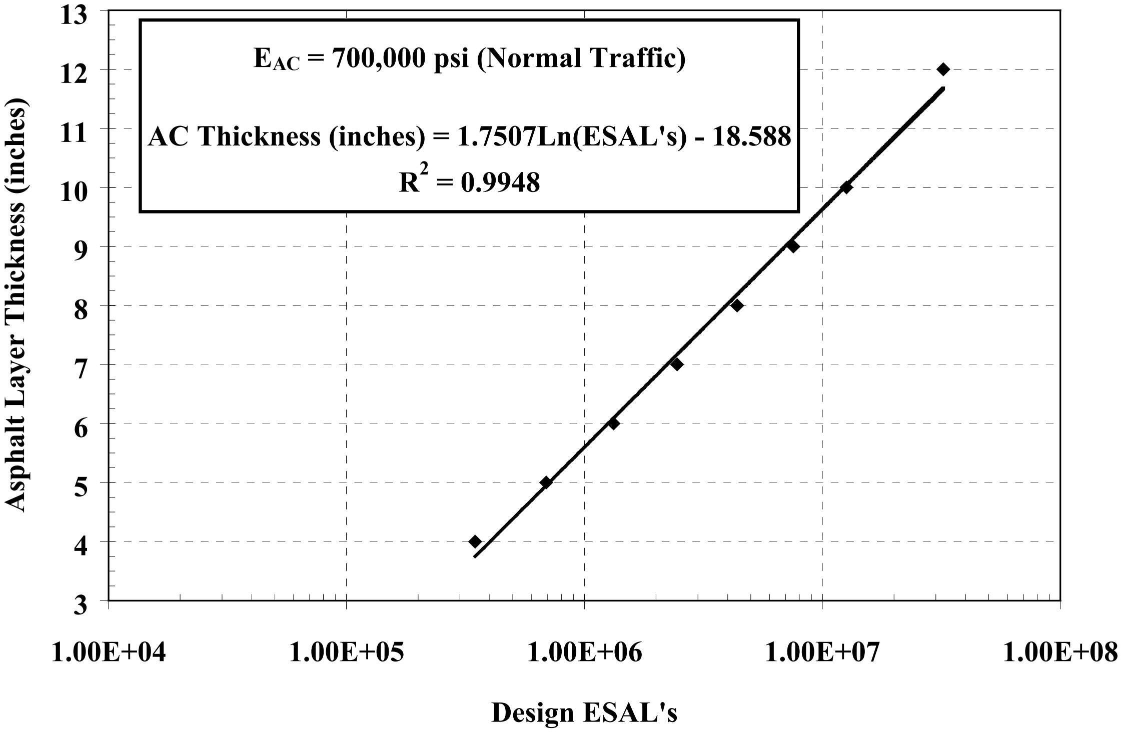


Figure 20 Number of Loading Repetitions (Design ESAL's) Until Fatigue Cracking Failure for Normal Traffic Speed for Empirical-Mechanistic Approach

The inspection of the above graphs clearly shows that the number of ESALs that a pavement can carry decreases with a decrease in speed. Thus, at places where a heavy vehicle stops, the pavement would deteriorate the fastest compared to other sections of the road. Temperatures above 70^0 F will aggregate this deterioration.

In Step 4, the ESAL for each bus for one run of the bus on a hypothetical pavement was determined. Now assuming a specific number of trips for each bus, the total ESAL over 20 years can be calculated. Then, the total ESAL for a vehicle can be input into each equation to obtain the required asphalt layer thickness for each condition. The actual cost of asphalt per unit volume can be obtained and multiplied with the assumed length, width and calculated thickness for various speeds and for each vehicle under consideration. The monetary value obtained can be used to compare the impact of different vehicles. For example, if the roadway is 20 miles long and the width of the slow lane is 8 ft, the total surface area is 844,800 ft^2 or 93,867 yd^2. Suppose the Trans Artic bus plies on this road, where there are 6 bus stops. The area of the bus stops can be approximately estimated to be 6*480 ft^2 (length 60 ft and breath 8 ft.) i.e. 2880 ft^2 or 320 yd^2. Thus, the area at which the bus plies at normal speed is 841,920 ft^2 or 93,547 yd^2. Suppose the total ESAL in twenty years for this bus was found to be 1.00E+07, then the required thickness of the asphalt layer at bus stops would be 11 inches while on the other areas the required thickness of pavement would only be 8 inches. Assuming an average cost of the asphalt layer of \$30 per yd^2 per 1 inch of height, the cost of the asphalt layer would be (\$30 x 320 yd^2 x 11 inches + \$30 x 93,547 yd^2 x 8 inches =

$22,556,880. Similar calculations can be performed for other vehicles, and results may be compared. If the number of heavy vehicles using the roadway segment, and as a result the design ESALs increase, a thicker asphalt layer will be required, resulting in an increase in cost. This extra cost may be attributed to the new heavy vehicle traffic.

Step 5

The cost responsibility of a heavy vehicle towards the pavement maintenance cost can also be calculated approximately if "extended data" for traffic as well as cost can be obtained. For a particular site for which maintenance cost information is available, the annual growth rate for heavy vehicle and all vehicle ESALs needs to be obtained. Total ESALs for each vehicle type can thus be estimated over a maintenance cycle (time period between two successive pavement maintenances). Review of the HCAS literature indicates that pavement maintenance is generally 100% attributable to load factors. Thus, the maintenance cost attributable to any vehicle may be considered as proportional to its ESAL. Maintenance costs attributable to buses may be estimated based on the bus ESALs percentage of the total ESALs.

***Outcome* 2**

The proposed method is flexible enough and may be used in cases in which data availability is limited. The outcome of the proposed method is an estimate of the contribution of various types of vehicles to pavement damage. If estimates for pavement maintenance expenditures are available for a particular roadway section, the proposed method allocates these costs as responsibilities to various types of vehicles.

CONCLUSIONS

This study is part of a comprehensive literature research effort, investigating the availability of methods for allocating roadway maintenance costs to different types of vehicle classes. Major findings of this part of the study indicate that a cost allocation study has not been performed for the state of New Jersey. Performing such a study is highly recommended, to develop a clear picture of the cost responsibility of each vehicle class and determine whether vehicles are currently charged their fair share of cost responsibility. Whether a simplified approach or a more detailed one is to be used depends on the availability of required data.

In the second part of this report, emphasis has been given in the review of methods that deal primarily with the impact of buses on highway pavements. This report details the literature search findings and presents a method based on the existing literature for quantifying the impact of buses and trucks on pavements.

Based on the results of the literature search and discussions with state DOTs and local authorities, it has been determined that not many studies exist, which deal explicitly with the impact of buses on pavements. Only two studies that treat this subject were identified, one performed by the City of Denver and one by the University of California. These have been reviewed in detail and are presented in the report. Based on these studies, a step-by-step procedure has been devised. A detailed discussion on minimum and extended data requirements is also presented in the report, along with information on data availability in New Jersey.

The proposed method is based on estimates of ESALs. It should be noted however that in the new pavement design method, which is expected to become effective in 2002, traffic will be considered in terms of axle load spectra. The old ESAL approach will no longer by used as a direct design input. It is suggested that a conversion method be developed, to estimate load spectra from ESALs and vice versa. In this case, the method would be used as described in this report.

REFERENCES CITED

1. Small A.K., Winston C., Evans C.A. Road Work. *A new Highway pricing and Investment Policy*. The Brookings Institution.Washington, D.C., 1989
2. Carey J. *Implementation of the Simplified Arizona Highway Cost Allocation Study Model*. Arizona Department of Transportation. Phoenix, Arizona. June 1,1999
3. *1997 Federal Highway Cost Allocation Study: Final Report*. U.S. Department of Transportation. Federal Highway Administration. 1997. http://www.ota.fhwa.dot.gov/hcas/final/toc.htm Accessed March 30,2001.
4. *State Highway Cost Allocation. Software Package*. Federal Highway Administration, Washington D.C. http://www.fhwa.dot.gov/policy/12-hmpg.htm Accessed May 12, 2001
5. Stower J.R, Reno A., Balducci P., Mingo R., Wolff H., Cohen H., Haling D. *Oregon Highway Cost Allocation Study.* Department of Administrative Services. Salem, Oregon. June 1,1999
6. Sinha K.C, Fwa T.F. *A Highway Cost Allocation Analysis at the State Level*. Transportation Quarterly. July 1987. Vol. 41, No. 3. p 347-364
7. Fwa T.F, Sinha K.C, Saha S.K. *Update Analysis of Highway Cost Allocation*. Transportation Research Record 1990. No. 1262. p 1- 11.
8. *Georgia Highway Cost Allocation Study. Special Report*. Research and development Bureau. Office of Materials and Research. Georgia Department of Transportation. Atlanta, Georgia. 1979.
9. *Update of Georgia Highway Cost Allocation Study FY 1981*. Research and Development Bureau. Office of Materials and Research. Georgia Department of Transportation. Atlanta, Georgia. 1981.
10. *Result of the Minnesota Highway User Coast Allocation Study*. Minnesota Department of Transportation, Minnesota. October 1990.
11. Seeds,S.B. *Flexible Pavement Design. Summary of the State of the Art.* http://www.nas.edu/trb/publications/millennium/00040.pdf . Accessed May 12, 2001.
12. Ekdahl, Peter. *A Sensitivity Test of Two Deterioration Models for Flexible Pavements.* Department of Technology and Society, Lund Institute of Technology, Lund University, Sweden, 1999 http://www.tft.lth.se/rapporter/prellicpe.PDF Accessed March 24, 2001
13. Team, Battellee. *Pavement and Truck Size and Weight Regulations, Working paper*. Comprehensive Truck Size and Weight Study. FHWA,US Department of Transportation, Feb 1995. http://www.fhwa.dot.gov/reports/tswstudy/TSWwp3.pdf Accessed March 24,2001.
14. Bell C. A., Randhawa S. U., and Xu Z. K. *Oregon Study Looks at Potential Pavement Damage from High-Pressure Truck Tires and Single-Tired Axles.* Road Engineering Journal , Dec 1 1997 http://www.usroads.com/journals/p/rej/9712/re971203.htm Accessed March 24, 2001
15. Ullidtz, P. *Pavement Analysis*, Elsevier, 1987.
16. Ullidtz, P. Modeling flexible Pavement Response and Performance Polyteknisk Forlag, Denmark, 1998.

17. Bhatti M. A, Lin B, Taylor P.C, Hart L.I. *PAVESIM: Simulation of Pavement Damage due to Heavy Vehicles*. Public Policy Center. University of Iowa, 1997
18. *Truck Pavement Interaction.* Federal Highway Administration. http://www.tfhrc.gov/pavement/truck/tech2.htm . Accessed 12 May 2001.
19. Gibby, R., Dawson, R, Sebaaly, P. *Local Urban Transit Bus Impact on Pavement.* Journal of Transportation Engineering. May/June 1996. Vol 122, No. 3. p 215-217.
20. Gibby, R., Styer R., Kitamura R. *Impact of Single Rear Axle Buses on Local Street Pavements*. Final Report. California Public Works Studies Program, 1991.
21. *Equivalent Single Axle Load (ESAL) Study*. Regional Transportation District (RTD) Busses. City and County of Denver, Colorado. Sept 14, 1994.
22. *Flexible Pavement Structural Section Design Guide for California Cities and Counties*. 3rd Ed. 1979. Caltrans, Sacramento, California.
23. Huang, Y.H. *Pavement Analysis and Design*. Prentice Hall Inc., New Jersey.1993.
24. *Highway Performance Monitoring System Field Manual*. Federal Highway Administration, Washington D.C. http://www.fhwa.dot.gov/ohim/hpmsmanl/hpms.htm Accessed March 16, 2002
25. *DataPave 2.0. Software Package*. Federal Highway Administration, Washington D.C. 1999

APPENDIX 1

Equivalent Single Axle Load (ESAL) Estimation

The ASSHTO procedures for ESAL estimation [23] are reviewed in order to get a clear understanding of the variables required to determine ESALs for buses.

An equivalent axle load factor (EALF) defines the damage per pass to a pavement by the axle in question, relative to the damage per pass of a standard axle load, usually the 18 kip (80 kN) single axle load. ESAL is then estimated as:

$$\text{ESAL} = \sum_{i=1}^{m} FiNi$$

where:

m = number of axle load group,
F_i = EALF of the i th load axle group, and
N_i = the number of passes of the i th load group during the design period

EALF depends on the type of pavement, thickness or structural capacity, and the terminal conditions at which the pavement is considered failed. One of the most widely used methods to determine EALF is the following AAHSTO regression equation:

$$\text{Log}\left(\frac{W_{tx}}{W_{t18}}\right) = 4.79 \log(18+1) - 4.79 \log(L_x + L_2) + 4.33 \log L_2 + \frac{G_t}{\beta_x} - \frac{G_t}{\beta_{18}}$$

where:

$$G_t = \log\left(\frac{4.2 - P_t}{4.2 - 1.5}\right),$$

$$\beta_x = 0.40 + \frac{0.081(L_x + L_2)^{3.23}}{(SN+1)^{5.19} L_2^{\ 3.23}},$$

W_{tx} = number of x-axle load applications at the end of time t
W_{t18} = number of 18 kip single axle load applications to time t
L_x = load in kip on single axle or one set of tandem axle or one set of tridem axle
L_2 = is the axle code, 1 for single axle, 2 for tandem and 3 for tridem
p_t = terminal serviceability
β_{18} = value of β_x when L_x is 18 and L_2 is 1.

SN = structural number which is a function of thickness and modulus of each layer and the drainage conditions of base and subbase.

SN can be directly obtained from the Long Term Pavement Performance program (LTTP) or can be calculated as follows:

$SN = a_1D_1+a_2D_2m_2+a_3D_3m_3$

where:

a_1,a_2,a_3 = layer coefficients of surface, base and subbase respectively
D_1, D_2, D_3 = thickness of surface, base and subbase respectively, and
m_2, m_3 = drainage coefficients of base and subbase

For rigid pavements the EALF equation is as follows:

$$\text{Log}\left(\frac{W_{tx}}{W_{t18}}\right) = 4.62 \log (18+1) - 4.62 \log(L_x + L_2) + 3.28 \log L_2 + \frac{G_t}{\beta_x} - \frac{G_t}{\beta_{18}}$$

where:

$$G_t = \log\left(\frac{4.5-P_t}{4.5-1.5}\right),$$

$$\beta_x = 0.40 + \frac{3.63(L_x+L_2)^{5.20}}{(D+1)^{8.46}L_2^{3.52}},$$

D = slab thickness in inches, and

$$\text{EALF} = \frac{W_{t18}}{W_{tx}}$$

Using the above formulas, pavement specific ESAL factors for various types of buses can be estimated.