Impact of Buses on Highway Infrastructure
Case Study for New Jersey State

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Buses are classified as heavy vehicles, and research has shown that heavy vehicles are mainly responsible for pavement damage and costs incurred to rectify the damage. Transit agencies must consider the pavement damage caused by a bus when choosing among different types of buses for procurement for certain corridors and deciding on the type of transit service for a corridor. Also, bus contribution to pavement damage should be considered in determining the appropriate amount of taxes and fees to be paid by this vehicle class. Currently, no tool exists to support such decisions. Pertinent literature was reviewed to determine the availability of methods for allocating roadway maintenance costs to buses. Two broad areas of highway impact–related literature, highway cost allocation studies and methods to estimate pavement deterioration resulting from vehicle–pavement interactions, were examined. A review of several state cost allocation studies showed that either equivalent single-axle loads (ESALs) or ESALS weighted by vehicle miles traveled were used to allocate pavement maintenance cost to various vehicle classes. Those studies, however, either accounted for buses by grouping them with other vehicles or did not account for them at all. Currently, no bus–pavement interaction models are available, although several mathematical and simulation models are available for truck–pavement interaction. Buses differ from trucks in load distribution, suspension, and travel characteristics. From results of the literature search a methodology, which uses industry standards and is minimal in data requirements, has been developed. With the use of data available in New Jersey, the application of this methodology showed that the maintenance cost attributable to buses in the state is about 2.4% of the total maintenance cost.

New Jersey Transit (NJ Transit) operates on 240 routes with 1,955 buses of its own and about 191 leased buses (*1*). The agency plans to replace and add about 1,900 buses to its fleet in the coming years. The choice of buses to buy and ply currently depends only on the purchasing, maintenance, and operating costs of these buses. But with 82.7 million mi covered annually, it is equally important to consider the pavement damage and consequently the pavement maintenance cost that is or would be incurred by the state as a result of the running of these buses on the roadways. Currently, NJ Transit does not possess a tool to determine these costs; that is the main factor that necessitated the research, results of which are presented in this paper.

The roadway system forms the backbone of New Jersey with more than 36,000 linear mi of roadway. This system is heavily used and thus requires regular maintenance, resurfacing, and sometimes reconstruction, to provide desired service. Pavement deterioration is influenced by the impact of natural forces such as temperature, humidity, and others, and by the damage caused by vehicles using the pavement over a period of time. Literature shows that pavement maintenance is primarily attributable to heavy vehicles, such as buses and trucks. The cost incurred to maintain the roadway infrastructure in serviceable condition is passed on to the road user. The estimation of how much damage is caused by each vehicle and how much the user should pay to cover this cost is a complex task. This task consists of three distinct steps:

1. Classify vehicles into categories.
2. Estimate pavement deterioration caused by each vehicle class or individual vehicles that results from vehicle–pavement interactions.
3. Estimate the maintenance cost to be allocated to various vehicle classes depending on their contribution to pavement deterioration.

The objectives of this study were

- Reviewing pertinent literature and determining the availability of methods for allocating roadway maintenance costs to buses.
- Developing a methodology that uses the current industry standards and is minimal in data requirements.
- Determining data availability and applying this method to New Jersey conditions.

Literature Review

To satisfy the first objective, a thorough review of pertinent literature was conducted. The New Jersey Department of Transportation (NJDOT) uses 13 vehicle classes in its traffic characteristics databases. This classification can be referred to on the NJDOT website (*2*). Heavy vehicles are classified as class 4 through 13, with class 4 consisting of buses and classes 5 through 13 consisting of various truck configurations. Two broad areas of highway impact–related literature, namely methods to estimate pavement deterioration as a result of vehicle–pavement interactions and highway cost allocation studies (HCAS), were reviewed.

There are several types of deterioration models. For detailed information on these models the reader is referred to the paper by Ekdahl (*3*). Two types of models applied in the pertinent literature are discussed:

- 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 explaining what happens inside the pavement materials. The equivalent single-axle load (ESAL) concept developed by AASHTO (*4*) is the

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most commonly used model of this type. An ESAL defines the damage to pavement per pass of the axle in question, relative to the damage per pass of a standard axle load, usually the 18 kip (80 kN) single-axle load.

• Mechanized models. These models exclude all empirical interference on the calculated pavement deterioration. They calculate all the effects on pavement structure purely mechanistically. Eleven models of this type have been developed and incorporated into the nationwide pavement cost model, which is used in the federal HCAS (*5*).

In this paper, we chose the empirical deterioration model based on ESALs developed by AASHTO because this is the most commonly and easily applicable method. Also, data for vehicles are easily available using ESALs, and New Jersey uses ESALs as a measure of a heavy vehicle's impact on infrastructure. It should be noted, however, that ESALs have several drawbacks:

1. They have been recorded from the road tests in Illinois and hence were not developed exclusively for New Jersey conditions. Although the models are considered to be applicable in New Jersey, they may not produce precise answers.
2. The ESAL method just relates cause and effect without considering the internal stress and strain mechanisms of the pavement.
3. ESALs do not consider all the impacts that climate and weather have on pavements.

Once the pavement deterioration model has been selected, it should be used to allocate maintenance costs to various vehicle classes. The federal government and some state governments have conducted HCASs for this purpose. An HCAS is an attempt to compare revenues collected from different highway users with the expenses incurred by highway agencies in providing and maintaining facilities for these users. Pavement maintenance cost is a component of the expenditure allocated to different vehicle classes. There are several sources that provide a list of federal and state HCAS reviews showing that buses are often classified with other vehicles or in some cases are categorized into one vehicle class, so that buses of different weights and types cannot be compared (*6–13*).

HCASs (*7, 14*) use various different approaches to allocate costs. All recent federal and HCASs use the cost-occasioned approach. In that approach, the physical and operational characteristics of each vehicle class are related to expenditures for pavement, bridge, and other infrastructure improvements. Expenditures and revenues are allocated to different vehicle classes in proportion to some measure of consumption and benefits like passenger car equivalents, vehicle miles traveled (VMT), or ESAL. Revenues and expenditures for each vehicle class are then compared to determine whether each vehicle class is paying its fair share of cost responsibility. If not, then recommendations are made to rectify the inequity. The cost-occasioned approach is used in the methodology proposed in this paper, as the most appropriate method to allocate maintenance and rehabilitation costs.

Further review of the literature showed that there are very few studies that deal explicitly with the effect of buses on pavement deterioration and their share of maintenance costs. A study conducted at the California State University (*15, 16*) had two primary objectives: (1) to determine typical axle weights for different types of buses and (2) to evaluate the impacts of these buses on local street pavement sections. The first objective was fulfilled by calculating the ESALs for the buses considered. One-time 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 (*17*), a statistical method based on pavement maintenance system (PMS) data, and visual observation. The study focused 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 the 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 a statistically significant likelihood that fewer street segments with bus service have very good condition ratings compared with 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 ability of sections to accommodate buses, the cost of arterials would be increased by less than 5%, whereas the cost of collectors would increase by 58%.

In the county and city of Denver study (*18*), the objective was to compare the impact of different types of buses used by the city of Denver on pavement. 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 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. Again, ESAL factors were determined, to compare the impact of buses on pavement, using two different methods: the nomograph from the Asphalt Institute and the AASHTO equivalency charts developed from the AASHTO Road Test.

The objective of the study conducted by Parsons Brinckerhoff for VIA Transit, the transit agency for Bexar County, Texas, was to determine the relative impact of roadway wear caused by the agency's transit vehicles (*19*). This objective is similar to one of the objectives of this paper. For simplicity, the vehicles were categorized into eight vehicle classes including a separate class for VIA transit vehicles. This class was further subdivided into four classes of transit vehicles used by VIA. Typical vehicles for each category were established, and data including the front and rear axle weights for fully loaded vehicles were collected for the typical vehicles. ESALs were calculated for each vehicle class assuming a simple fourth power equation for a 10-in. rigid pavement (*20*). This value was multiplied with the annual VMT for each vehicle class to estimate the impact of each vehicle class on the entire roadway system. Finally, the percentage of the total ESAL miles for each vehicle class was calculated to allocate pavement maintenance cost to each vehicle class. The analysis showed that the ESALs for VIA transit buses range from 3.39 ESALs to 0.37 ESALs and VIA transit vehicles account for less than 2% of the damage caused by vehicular traffic. Bus VMTs were only 0.02% of the total VMT.

Proposed Approach and Data Requirements

The analysis of bus impact on pavements may be conducted at two levels, system level and individual level. At the system level, the impact on pavement and the maintenance cost induced by all buses in a network should be estimated. At the individual level, the impact and cost due to individual buses can be used to compare buses or compare transit alternatives for a corridor. In this 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, is presented next. Applications of the proposed method to New Jersey highways are also presented within each step.

Methodology

An outline of the proposed methodology is shown in the flowchart of Figure 1. 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 they appear in the flowchart.

Data Requirements

Vehicle data used are as follows:

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

For a more accurate calculation of axle loads (*15, 16*) additional data required included

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

For system-level analysis, either axle weights or average ESAL value of representative vehicles for each vehicle class is required.

Pavement data consist of the following:

- Terminal serviceability;
- Type of pavement;
- Length of corridor and area of bus stops in the corridor;
- Flexible, rigid, and composite pavement as a percentage of the total pavement length; and

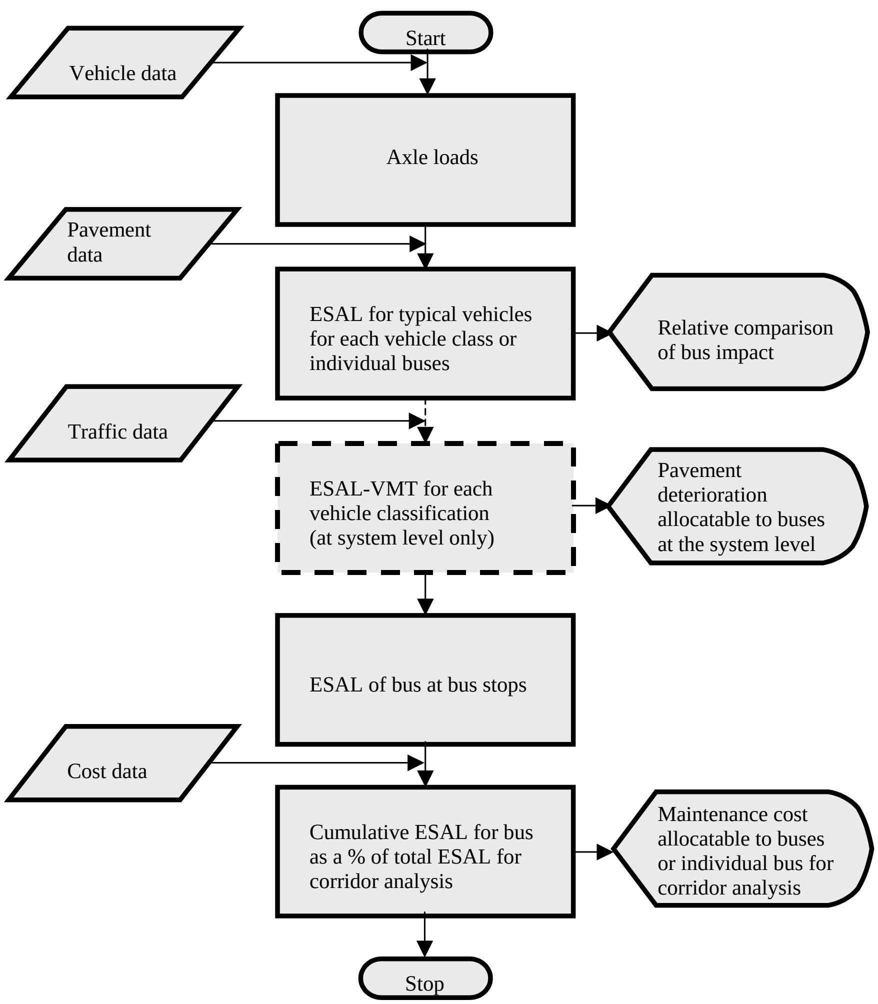

FIGURE 1 Proposed methodology.

• Design structural number (SN) for flexible pavement or depth for rigid pavement, if available.

If the SN were not readily available, then the following additional information would be required to calculate it:

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

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 bus over a section of roadway, and
- Total ESAL for the current period.

Additional data requirements include the traffic growth rate if the analysis period is greater than 1 year and the bus growth rate for the same period.

For system-level analysis, VMT by vehicles in each vehicle class is required.

For cost data, the cost per volume of surface layer for each pavement type would be included. Additional data required would be

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

The minimum data required, as given, would be referred to as "basic data," and the additional data required will be referred to as "extended data." A summary of these data requirements and their availability in New Jersey is shown in Table 1.

For the current application, not all extended data were available. For example, although an approximate estimate of maintenance cost can be conducted with the basic data, extended data are required for accurate estimation of maintenance cost attributable to buses. NJDOT collects pavement data for its PMS and also reports additional data such as traffic and cost data for various sections, in the Long-Term Pavement Performance (LTPP) database. LTPP data were accessed using the DataPave CD-ROM (*21*). Although data for several sections were available, none of the sections had the complete set of data required for the analysis.

Procedure

According to the literature findings presented so far in this report, the vehicles were classified into 13 classes. Data for this classification are easily available from NJDOT. ESAL is often the parameter used to allocate load-related costs. Thus, estimating ESALs for different types of vehicle classifications or individual buses is a very important first step in determining cost responsibility for

TABLE 1 Data Availability in New Jersey

Data Requirements	Data Availability/Source
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	Vehicle manufacturer
Unladen weight of the vehicle	Vehicle manufacturer
Vehicle weight when fully loaded	NJ Transit bus data * Not readily available in this application, but could be computed from data obtained
Distance between front bumper and front axle	Vehicle 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	State DOT - N/A for the current application
Layer coefficients of each layer	State DOT - N/A for the current application
Thickness of each layer	State DOT - N/A for the current application
Drainage coefficients for base and subbase	State DOT - N/A for the current application
Bus schedule for peak and off-peak periods on weekdays	NJ Transit
Bus schedules for weekend	NJ Transit
Total ESAL for the current period	LTPP database
Traffic growth rate for the analysis period	NJDOT website (*1*) *Available online only for year 2000
Bus or truck growth rate for the analysis period	NJ Transit
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

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, which are typically available from the vehicle manufacturer, are 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 computer program, like the one used in the University of California study (*15, 16*). Alternatively, an average passenger weight (e.g., 150 lb) 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.

An example application of this procedure for various types of buses operated by NJ Transit is shown in Table 2. In this example, it was assumed that pavement terminal serviceability index is 2.5 and SN is 5, which are typical values. Data provided by NJ Transit are shown in the first 15 rows of the table. These data include vehicle design characteristics and axle weight. The axle weight is given for typical values, shown as Weights Represented in the table. For example, the typical load for the two commuter buses is the seated load, whereas for the other types of buses, it 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. To estimate ESALs for crash load, an average weight per passenger of 150 lb 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 it was distributed evenly among the vehicle axles.

For system-level estimation, it would be desirable to have the axle weight data and the number of axles for the representative vehicles

TABLE 2 New Jersey Transit Bus Data and ESAL Estimate

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 Tax Axle Tires	2	2	2	2	n/a	n/a
Weights Represented	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

* ESALs for typical bus loads, given as weights represented
** ESALs for fully loaded buses, given as crush load (150 lb per passenger, evenly distributed over the vehicle's axles)

in each of the 13 classifications. These data could be used in Step 2 to accurately calculate the representative ESAL for each vehicle classification. These data were not available for the purpose of this study.

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 the University of California study (*15, 16*), or a more detailed one, such as the AASHTO procedure (*4*), may be used. 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. Bus ESAL estimates for the NJ Transit vehicles for flexible pavements using the AASHTO procedure are shown in the rows labeled Total Bus ESAL in Table 2.

Outcome 1 At this point, a comparative analysis may be performed on the relative impact of different types of buses. The ESALs of different vehicles are used to estimate 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 2 indicate that the Volvo type A and B buses are expected to cause more damage on the pavement considered in the analysis, compared with the other types of buses operated by NJ Transit.

Step 3 This step is required in a system-level analysis. The average ESAL for each vehicle classification indicates how much damage that vehicle could cause by its one run on the pavement. However, it does not indicate how much of the infrastructure is used by the vehicle. VMT is a good indicator of this. Thus, the product of ESAL and daily VMT is a good indicator of the impact of a vehicle class on the entire roadway system.

NJDOT publishes a summary of annual VMT by each vehicle class. Data for the year 2000 (*22*) were used for this analysis. Table 3 shows the analysis performed for New Jersey at the system level, assuming that 70% of pavements are flexible pavements. NJDOT also publishes annual average ESAL for heavy and light trucks for individual routes in New Jersey (*23*). FHWA Vehicle Class 5 consists of light trucks, and Vehicle Class 4 consists of buses. Vehicle Classes 6 to 13 consist of heavy trucks. Because data on typical vehicles for each vehicle classification were not available, the average ESAL for all sections for heavy trucks and light trucks was calculated individually and was used as representative of each vehicle classification for the year 2000. Then the product of ESAL and daily VMT and the percentage of the total ESAL miles for each vehicle class were calculated; they are shown in Table 3.

Outcome 2 Under the assumption that heavy vehicles are primarily responsible for pavement damage in New Jersey, the foregoing system-level analysis shows that about 2.4% of the pavement damage and thus the associated maintenance and rehabilitation costs can be attributed to all buses in New Jersey, including NJ Transit buses. With the use of typical vehicle data and VMT data for NJ Transit buses, the estimation can be done in a similar fashion for NJ Transit buses alone. In this case, the increase in ESAL due to the decrease in speed at bus stops may also be considered.

Step 4 Buses have a unique travel characteristic: they frequently stop at bus stops. Research has shown that this action causes great damage to the pavement at bus stops (*15, 16*). The following analysis, considering a hypothetical pavement section, demonstrates this fact.

The hypothetical highway pavement section is a three-layered pavement section, with an asphalt layer, a nonstabilized base layer, and a subbase layer on a subgrade. The thickness of the aggregate layers represents some typical pavement sections in New Jersey. A single wheel load of 9,000 lbf is assumed to be applied on the pavement section, for this represents load on a single wheel of an 18-kip single-axle load. This pavement was analyzed using the 1993 AASHTO pavement design procedure (*24*), which is an empirical design method. The procedure is based on determining an 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. The typical values of these parameters in New Jersey are 0.14 for base layer coefficient (a_2), 0.11 for subbase layer coefficient (a_3), and 1.0 for base and subbase layer drainage coefficient. These parameters are also recommended as default parameters if information on the pavement system is unknown.

The layer coefficient (a_i) is a parameter that has been statistically derived at the AASHO road test. The base layer coefficient and the subbase layer coefficient are as shown in Figure 2 and remain constant throughout the analysis. The asphalt layer coefficient is varied.

TABLE 3 System-Level Analyses of Buses

FHWA Vehicle Class	Avg. ESAL	Daily VMT (1000s)	ESAL-miles	Percentage
4 (buses)	0.23	1,530	351900	2.40
5	0.23	5,015	1153450	7.87
6	1.3	1,882	2446600	16.70
7	1.3	591	768300	5.24
8	1.3	2,065	2684500	18.32
9	1.3	3,778	4911400	33.52
10	1.3	998	1297400	8.85
11	1.3	488	634400	4.33
12	1.3	160	208000	1.42
13	1.3	151	196300	1.34
		Sum	14652250	100.00

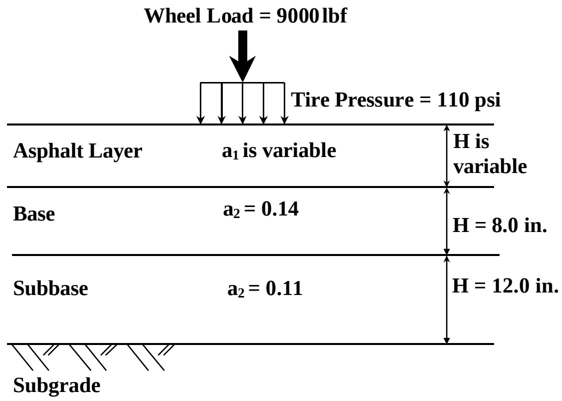

FIGURE 2 Pavement section used for comparative analysis.

The 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 layers, also highly temperature dependent. Work conducted by Van Til et al. (*25*) provided a guideline to convert the resilient modulus of asphalt, determined at 70°F, to a structural coefficient that can be used in the AASHTO design procedure. A regression model developed is as follows:

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

where a_1 is the asphalt layer coefficient and M_R is the resilient modulus of asphalt.

Therefore, for the asphalt layer, the resilient modulus was chosen to be evaluated at one temperature (70°F). However, it was analyzed over different traffic loadings:

1. Stop and go (less than 4 mph), with M_R of 300,000 psi;
2. Slow (approximately 15 mph), with M_R of 500,000 psi; and
3. Normal conditions (approximately 60 mph), with M_R of 700,000 psi.

A sensitivity analysis for the hypothetical pavement section was conducted using the AASHTOWare DARWin computer program. The program, based on the AASHTO design procedure, allows one to easily vary parameter values and evaluate the pavement system's sensitivity to these parameters. The program design criteria were set to determine the number of design ESALs for the chosen pavement section, 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 the values specified in the 1993 *AASHTO Guide for Design of Pavement Structures* (*24*). These parameters are default parameters provided in the computer program, except for the effective subgrade resilient modulus, which needed to be input by the user. Therefore, the sensitivity analysis is based on varying the asphalt thickness and the asphalt resilient modulus, which is a function of the traffic speed for pavement temperature of 70°F. Results of the analysis are shown in Figure 3. Figure 3 shows that, as expected, as the resilient modulus of the asphalt increases (or traffic speed increases) so does the design ESAL for the same asphalt thickness. Inspection of the graphs clearly shows that the number of ESALs that a pavement can carry decreases with a decrease in speed. Thus, at sections where heavy vehicles stop, the pavement would deteriorate faster compared with other sections of the road. Temperatures above 70°F will aggregate this deterioration.

While calculating the ESAL due to buses for a corridor analysis, the increase in ESAL at bus stops must be considered. The methodology as described could be used to calculate the ESAL at less than 4 mph for each bus plying in the corridor considered. Then the percentage of roadway used as bus stop may be calculated, and the weighted ESAL using percentage of normal road and percentage of bus stop may be estimated. For example, consider a roadway section 200 ft long with 1 bus stop of 50 ft. Let the ESAL at normal condition for the bus be 3 and at bus stops 4. The percentage of bus stop is 50/200, that is, 25%. Therefore, the weighted ESAL would be $0.75 * 3 + 0.25 * 4 = 3.25$. This is the weighted ESAL for the bus in the corridor under analysis.

Step 5 ESALs estimated so far are representative of a single pass of a vehicle over the pavement. For corridor analysis, traffic data are required to determine the cumulative ESALs over an analysis period. In New Jersey, these data are available from weigh-in-motion stations at several locations. For buses, the number of passes at a particular location over the analysis period may be calculated from the weekly transit schedule. On the basis of information on bus peak and off-peak and weekday and weekend scheduling and knowledge of the 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. The number of passes obtained for each vehicle type is multiplied with its ESAL and the results are summed to obtain the annual ESAL for a particular roadway segment. For an estimate over a maintenance cycle (time period between two successive pavement maintenances), a traffic growth factor should be considered in the analysis.

The cost responsibility of a bus toward the pavement maintenance cost may be calculated if extended data for traffic as well as cost can be obtained. In a simplified approach, load-related infrastructure expenditures may be allocated to different types of vehicles based on their cumulative ESALs. 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 3 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 paper 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 performing a cost allocation study is very important in developing a clear picture of the cost responsibility of each vehicle class and determining whether vehicles are currently charged their fair share of cost responsibility. Whether a simplified approach or a more detailed one is to be

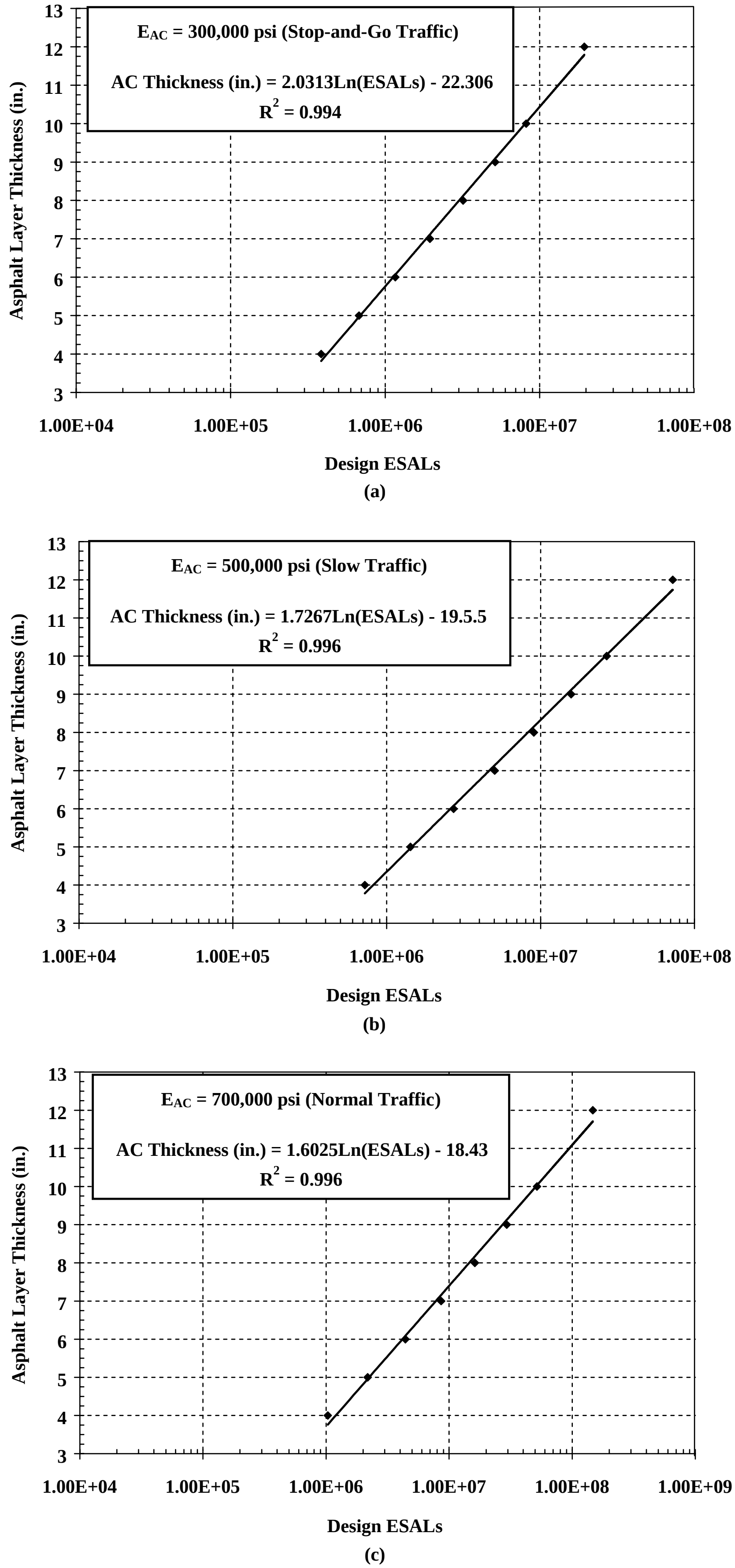

FIGURE 3 Design ESAL versus asphalt thickness for (*a*) stop-and-go traffic, (*b*) slow traffic, and (*c*) normal traffic.

used depends on the availability of required data, as described in the previous section.

From the results of the literature search and discussions with state DOT and local authorities, it has been determined that not many studies exist that deal explicitly with the impact of buses on pavements. This paper presents a step-by-step approach for estimating the impact of buses on highway pavements, along with an application of this approach to New Jersey highways. The proposed method is based on estimates of ESALs. It should be noted, however, that in the new pavement design method, which became effective in 2002, traffic will be considered according to axle load spectra. The method presented in this paper may still be used without major modification, by incorporating the method that will be developed to estimate load spectra from ESALs and vice versa.

According to the case study results, it has been shown that

1. Buses do cause significant damage on pavements, which based on the estimated bus ESALs is often comparable to the damage caused by trucks.
2. Bus stop-and-go conditions have a more prominent impact on pavements.
3. Maintenance costs attributable to buses in New Jersey account for about 2.4% of the total maintenance costs.

Buses are typically ignored or dealt with at a very aggregate level in highway cost allocation studies, and emphasis is given only to trucks. The reason stems from the usually small percentage of bus compared with that of truck and other vehicle traffic. However, explicit consideration of buses and use of a method such as the one presented in this paper is deemed necessary for the purpose of performing a comparative evaluation of different types of buses, comparing transit alternatives in an economic analysis of a corridor study, and allocating highway pavement maintenance costs to different users.

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