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EVALUATION OF TRUCK IMPACTS ON PAVEMENT MAINTENANCE COSTS

by

R. Gibby
Department of Civil Engineering
California State University - Chico
Chico, CA 95929

R. Kitamura
Department of Civil Engineering
University of California, Davis
Davis, CA 95616

and

H. Zhao
Department of Civil Engineering
University of California, Davis
Davis, CA 95616

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ABSTRACT

The objective of this study is to determine the factors that influence pavement maintenance costs of California state highways, and to evaluate the impact of heavy truck traffic on maintenance cost. To this end, over 1,100 one-mile sections of state highways are randomly sampled, and data from various sources are integrated to form a data base containing the information on traffic, weather, geometric conditions, and pavement maintenance costs for the sample sections.

Following an extensive explorative analysis of the data, a model of pavement maintenance cost is statically formulated. The most significant finding is that heavy truck (five or more axles) traffic has a much larger impact on pavement maintenance cost than does light truck traffic or passenger car traffic. The estimation results indicate that, on a typical roadway, the average annual maintenance cost per heavy truck per day amounts to $7.60 per mile per year, while the corresponding cost per passenger car is approximately 8¢. The study further shows that one additional heavy truck per day will cost annually an additional $3.73 per mile of a roadway for pavement maintenance. An increase by 50 heavy trucks will cost $183.10 per year per mile. The corresponding cost increases due to passenger car traffic are 4¢ and $2.18 per year per mile, respectively. This study thus establishes that one heavy truck is approximately equivalent to 90 light trucks or passenger cars in terms of its impact on pavement maintenance cost.

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DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California. This report does not constitute a standard, specification, or regulation.

INTRODUCTION

One important highway preservation issue which has surfaced in recent years is the rationale to allocate maintenance costs among the various road users. State Departments of Transportation in the United States frequently prepare cost allocation studies which probe this subject to aid in the development of revenues to support budget requests. It is well recognized that heavy truck traffic causes most of the damage to pavements and is the key factor in the roadway pavement design procedures. However, the extent of truck influence on pavement maintenance costs has not yet been satisfactorily supported. For example, current pavement cost allocation methods fail to incorporate environmental factors such as climate.

This study is proposed to develop a pavement maintenance cost model while taking into account environmental and geometric factors as well as traffic variables. The objective of the study is to identify the factors influencing pavement maintenance costs, and to evaluate the impact of heavy truck traffic on the maintenance cost of California state highways.

A statistical approach is taken in this study. Using a random sample of over 1,100 one-mile sections of state highways, and data retrieved from various sources, pavement maintenance costs are examined in multivariate statistical contexts. It is considered crucial in this study that this examination be performed while taking all relevant factors into consideration. A data base was prepared to support this examination by integrating the traffic, weather, geometric, soil type, and pavement maintenance cost information for the respective sample sections.

Following a brief review of the literature in the next section, the following section documents the procedure of data file preparation in detail. The results of the model estimation effort is presented in the fourth section together with the description of the variables used in the analysis and basic statistics portraying the data file. Using the estimation results, the average pavement maintenance costs, and additional cost due to an increase in traffic, are evaluated and the relative impacts of heavy trucks and passenger cars are determined. The fifth section offers a summary of the major conclusions while the major recommendations are contained in the final section.

LITERATURE REVIEW

With the intent of uncovering literature which may have some bearing on the issue at hand, state, national and international literature was consulted. The following comments summarize the articles found to be most relevant to the issue of pavement maintenance cost allocation.

Contemporary interest in this topic started in 1978 and 1979. The Congressional Budget Office (CBO) [1, 2] reviewed and discussed the subject of allocating all pavement maintenance costs by using an axle-load-equivalent approach. This method allocates pavement costs to classes of vehicles on the basis of pavement wear or deterioration they cause. It makes use of the extensive AASHO road test, conducted in the late 1950's, information on the relative amounts of pavement wear for which various types of vehicles were responsible. In particular, it was found that heavy trucks are responsible for pavement wear equivalent to that caused by an enormous number of automobiles. Two exceptions to using axle-load equivalents in pavement cost allocation exist: cost attributable exclusively to environmental factors, and costs of a permanent, nondepreciating nature. Some questions regarding environmental factors, pavement depreciation, and AASHO road test reliability, still need to be answered. However, the CBO concluded that costs should be allocated in the same way as in paving the road itself.

In 1984, the Federal Highway Administration (FHWA) produced a guide [5] intended as a resource document to be used by the states in constructing their own cost allocation studies. It does not recommend any specific allocation method, but rather explains the strengths and weaknesses of various methods. As a reference, this guide documents the information and analyses resulting from the federal cost-allocation study of

May, 1982. This source did not reveal significant information regarding pavement maintenance cost allocation methodology.

The State of Indiana in 1984 required a model estimating pavement routine maintenance (i.e., patching and crack sealing) costs [4]. A major purpose of the study was to predict costs without special purpose data. The average daily traffic (ADT) values were converted to equivalent single axle loads (ESAL), an index that converted all vehicle weights and types to representative 18K ESAL's. The best cost model for reinforced concrete pavement sections was as follows:

$$\log(\text{Cost}) = 0.005(\text{Age}) + 0.54\,(\log(\text{ESAL})).$$

Another model was available for resurfaced reinforced concrete pavement:

$$\log(\text{Cost}) = 0.032(\text{age}) + 0.57(\log(\text{ESAL})).$$

Both models gave very good results. Major conclusions included:

1. There is a strong correlation between routine pavement maintenance costs and pavement age and amount of traffic accumulated (ESAL), and
2. Both models yielded estimated costs close to the actual values. This was true for both reinforced concrete and resurfaced reinforced concrete sections.

In 1984 the FHWA [5] explained in detail highway cost allocation assignments and a few new methods used to make these assignments. A new cost allocation method, the minimum pavement thickness method, was recommended for proportioning thickness costs for new pavements. This method utilizes each vehicle's ESAL value to estimate thickness responsibility. An incremental approach is used to assign new pavement costs. The minimum pavement thickness method assigns heavy trucks more new pavement costs than any of the compared incremental approaches. Another approach, using the AASHO road test equations for 100% of costs, over-assigns costs to heavy vehicles. The effects of rehabilitated pavement assignment methods on overall cost assignments were also compared.

The basic purpose of highway cost allocation methodology in New Zealand [6] was to implement the taxation principle that the "user pays". Traditionally, New Zealand had allocated cost among the driver, road space and pavement strength requirements. This 1984 material reported a departure from the "fourth power rule" (sum of the fourth power of each axle weight divided by 10,000) in favor of the "third power rule" for apportioning pavement wear costs. The primary result of the effort was an allocation of cost based on a fee assessment which was, in turn, based on equivalent design axles, truck fuel and large tires. The allocation breakdown was 22%, 54%, and 24%, respectively. This reference also raises an interesting question: Should non-user benefits, derived from pedestrians, cyclists, flood control and public utilities, be factored into the cost allocation models?

The United Kingdom's Department of Transport, in 1984 [7], allocated all roadway costs based on a type of "Delphi" concept by using the opinions of highway engineers and research scientists. The allocation cost of 1.6 billion pounds was weighted according to the following scheme:

Vehicle mileage	36%
Gross vehicle weight mileage	14%
Standard axle mileage	36%
Pedestrians	14%

A standard axle in tons was calculated from the fourth power rule. Approximately 44% of all road costs were allocated among the three major maintenance activities: reconstruction and resurfacing; surface skid improvement; and pothole and minor repair. Of the 44%, 28% were allocated to reconstruction and resurfacing by standard axle mileage, 6% to surface skid improvement by vehicle mileage (0.8 weight) and by gross vehicle weight mileage (0.2 weight) and 10% to pothole/minor maintenance by vehicle mileage.

In California, SYDEC, Inc., in 1987 used a Delphi panel composed of selected experienced California Department of Transportation (Caltrans) maintenance personnel [8]. The Delphi process submitted questions to this panel of experts regarding the amount of pavement maintenance cost attributable to various highway users. The results of this Delphi process were then averaged with results from the Caltrans Transportation Laboratory work. The laboratory work results were developed for the purpose of design, rather than maintenance. Approximately 66% of pavement maintenance were allocated to heavy (five or more axles) vehicles while the balance was attributed to lighter vehicles.

In summary there has been little done using analytical techniques in the literature relevant to the issue of highway pavement maintenance cost allocation methodology. In Indiana, analytical cost allocation has been performed for routine pavement maintenance [9]. But these costs did not include maintenance efforts toward addressing poor ride quality, structural failure or preventative maintenance actions, which are major maintenance activities in California. Total pavement maintenance cost allocations has been done in several places using the concept of the Delphi process, which, again, is not an analytical method.

DATA FILE PREPARATION

The data file used in this project is an integration of various pieces of information obtained from several data sources. The process of data file preparation is summarized in this section.

Caltrans' data acquired for the project include:

1. 1986 annual average daily traffic classification count data on the California state highway system [10],
2. maintenance costs for selected maintenance measures by control section for fiscal years 84-85, 85-86, and 86-87 [11], and
3. highway geometric information [12].

In addition, an established set of weather classification categories is used for this study [13-15].

Traffic Data

A sample of roadway segments was prepared for the study by randomly selecting a one-mile section for every 15 mile segment of the state highway system. The beginning one-mile section was normally selected as the first section of each route. Some sections were chosen with somewhat different spacing when upstream and downstream traffic volumes differed substantially and the homogeneity of the sample section was questionable. The sampling process resulted in a total of 1,152 sample sections. The distribution of sample sections across the counties is illustrated in Table 1.

For each sample section, the following variables were extracted from the Caltrans report on annual average daily traffic classification count data [10]:

route number,
district,
county,
postmile,
total vehicle annual average daily traffic (AADT),
total truck AADT
total 5^{+}-axle truck AADT, and
equivalent single axle loadings (ESAL).

The nature of the traffic count data is specified in the traffic volume file as either "verified," or "estimated". "Verified" means the count is based on actual field data while "estimated" values are obtained using data from nearby verified sites. The number of sample sections with 84-85, 85-86, and 86-87 verified traffic counts are 96, 115, and 95, respectively.

Weather Data

Detailed descriptions of the climate conditions prevailing at the sample sections were obtained by establishing weather categories and also by using weather data from the nearest stations. The references used to establish weather classifications include the following:

California's Many Climates [13],

Characteristic Weather Phenomena of California [14], and

Weather of Southern California [15].

Synthesizing weather categories presented in these references, the following four weather classes were established:

maritime,

mountain,

desert, and

valley.

In addition to this climate type classification, the following measurements were incorporated into the data file:

annual precipitation,

average annual temperature,

average December temperature, and

elevation.

December average temperature is used in this study because a previous study [16] found strong correlation between this variable and highway maintenance costs.

The data for each sample highway section were obtained from that weather station, among the 120 survey stations that provide weather information for the state, whose coverage area contained the sample roadway section. Accordingly weather data vary from section to section within each weather category.

Maintenance Cost Data

The Caltrans highway maintenance cost data base for selected maintenance measures by control section [11] was used in this study. The data for fiscal years 84-85, 85-86, and 86-87 were available to prepare the cost data file. Maintenance cost information was divided into two categories,

flexible pavement, and

rigid pavement.

Fortran programs were written to extract the cost data from these Caltrans files for the 1,152 sample sections and match them with traffic and weather data. The data file resulting from the extracting and matching effort contained information on labor hours, labor dollars, equipment dollars, and material dollars.

Geometric Data

The geometric data used for this study include:

roadway functional classification,

pavement type,

number of lanes,

shoulder width,

traveled way width, and

pavement age

where pavement age is measured in terms of the recorded number of years since the last major pavement work. These data were extracted from the California State Highway Log [12] manually and matched with the rest of data for the 1,152 sample sections.

Limitations of the Data File

Every effort was made to attain the highest possible data quality in the preparation of the data file for this project. However, because of the problems in the existing data sources and the limited time resources available to the project, the data file is subject to certain limitations:

a) Verified traffic data were not available to all of the 1,152 sample sections. For 58% of the sample sections, traffic data "estimated" by Caltrans are used.

b) Verified traffic data were not necessarily available for the years for which maintenance cost data were available. Of the 42% of the sample sections, for which verified traffic data were available, only 306 sections have data from 84-85, 85-86, or 86-87.

c) No computer-retrievable data sources apparently exist for certain geometric characteristics, structural characteristics, terrain and drainage, traffic regulations, and roadway maintenance and improvement histories.

d) Maintenance costs may have been prorated over a long span of roadway.

e) Roadway rehabilitation works may not have been classified as such (possibly due to funding categories) when determining the year of the last major pavement work, which may have led to incorrect identification of the pavement age in the data file.

These limitations must be kept in mind when interpreting and generalizing the results of this study presented in the next section.

ANALYSIS OF DATA

An extensive set of variables (see Tables 2 and 3) was examined in the study to identify the factors which contribute to pavement maintenance cost (the VMS version of the BMDP statistical software package was used in the statistical analyses presented in this paper). Following a preliminary analysis of the distributive characteristics of the variables in the data file using histograms, bi-variate correlation coefficients, and contingency tables, pavement maintenance cost models were developed through multiple linear regression analysis.

Two types of models, linear and multiplicative, were considered and numerous model formulations were tested in the process of model development. The results of the analysis indicated linear models in general offered poor fits with occasional negative model coefficients that could not be theoretically supported. Multiplicative models, on the other hand, offered good fits and significant coefficients with theoretically consistent signs. Therefore only the results of the analysis using multiplicative models are presented in this paper.

Results of Model Estimation

Alternative models were estimated using the 1,007 sections in which the total 1984-87 pavement maintenance expenditures were not zero and data were complete. The following discussion, therefore, is concerned with the variations in pavement maintenance costs during 1984 through 1987,across those one-mile sections where routine maintenance work was performed at all during that period.

The estimated coefficients of the best model chosen in the analysis are summarized in Table 4 together with goodness-of-fit statistics. The coefficient (β) applies to the variable as a power. For example, the constant term, 17.66, and the coefficient, 0.207, of ln(HT-AADT) imply that the dependent variable, ln(TOTALCOST), is expressed as

$$\ln(\text{TOTALCOST}) = 17.66 + (0.027)\ln(\text{HT-AADT}) + \ldots$$

or

$$\text{TOTALCOST} = (4.67 \times 10^{7})\,(\text{HT-AADT})^{0.207} \ldots .$$

The dummy variables (to which log-transformation is not applied) in these multiplicative models takes on values of 1.0 or 2.718 (= e). For example, DISTRICT2 will take on a value of 2.718 for a roadway segment if it belongs to District 2, and a value of 1.0 otherwise. District 2 is the northern central and northeastern portion of the state. The variable does not influence the dependent variable if its value is 1.0. On the other hand, if its value is 2.718, it factors TOTALCOST by exp(β), where β is the coefficient of this variable. For example, the coefficient, 0.60, of DISTRICT11 implies that the total maintenance cost is multiplied by 1.82 (= exp(0.601)), or is approximately 80% more, in

District 11. District 11 is the most southern part of California including San Diego and desert counties.

The most important finding is that the coefficient of heavy truck annual average daily traffic (ln(HT-AADT)) is positive and highly significant (heavy trucks are defined in this study as those with 5 or more axles). In fact this variable has the largest t-statistic, implying that it is the single most important variable that influences pavement maintenance costs. The estimated coefficients also indicate light truck and passenger car traffic does not significantly contribute to pavement maintenance costs.

It is also important to note that climate variables play only a minor role in this model. Many indicators of weather were examined during the model development (AATEMP, DECTEMP, RAINFALL, ELEVATION, MARITIME, MOUNTAIN, DESERT, and VALLEY). Only two, AATEMP and MOUNTAIN, are significant and used in the final model. The results suggest that the variation in pavement maintenance costs due to climatic differences is minor in California. Further investigation is ongoing to validate this conjecture while considering a more extensive set of climate variables and their transformations.

The variables in the model other than the traffic and climate variables are pavement type (BRIDGE), functional classification (MNCOLLCTR), roadway geometry (SHOULDER, and NOSHOULDER), pavement age (AGE), and indicators of districts (DISTRICT2 and DISTRICT11). The coefficients of MOUNTAIN and MNCOLLCTR indicate that, other things being equal, fewer maintenance dollars tend to be expended in mountain areas and also on minor collectors. The dummy variable for no shoulder (NOSHOULDER) indicates that, other things being equal, maintenance cost tends to be smaller for roadways with no shoulder.

The inclusion of the district indicators in the model suggests that maintenance cost per unit distance varies by district, presumably because of the differences in maintenance practice. The estimated model coefficients reveal that maintenance costs per unit distance tend to be higher in Districts 2 and 11, by 93% and 82%, respectively. District 2 is the sparsely populated northeastern portion of California, while District 11 is the extreme south.

The age variable has a positive coefficient as anticipated. However, its value is very small and only marginally significant with a t-statistic of 1.8. The result suggests that the cost of routine maintenance does not vary substantially by the age of the pavement, given that maintenance work is performed at all. These results were confirmed in a weighted least squares analysis performed to account for possible heteroscedasticity.

Similar modeling exercise was performed using 1,079 sample sections comprising all sections with complete data, including those 72 sections where 1984-87 maintenance costs were recorded to be 0. While the coefficients of heavy truck traffic (HT-AADT) were very similar between the two samples (0.207 and 0.210), discrepancies emerged in terms of the variables included and their coefficient values. This result suggests whether or not maintenance is performed at all on a given section of a roadway, is governed by factors that are different from those influencing the cost of maintenance work. In addition, the estimated coefficient of light truck (less than five axles) traffic was very small in this estimation result.

Evaluation of the Maintenance Cost Due to Heavy Truck Traffic

One of the properties of the multiplicative model used in the analysis is that each coefficient represents the sensitivity (or "elasticity") of roadway maintenance cost to changes in the explanatory variable. For example, the coefficient value of 0.21 for heavy truck AADT implies that a 1% increase in heavy truck AADT leads to a 0.21% increase in maintenance cost. Using the estimated coefficient values, a 1% increase in light truck or passenger car AADT will result in a much smaller 0.06% increase in maintenance cost.

The contribution of each additional vehicle on the absolute dollar cost of maintenance can also be evaluated using the estimated model. The results of this estimation, summarized in Table 5, indicate that, on a typical roadway section, each additional heavy truck per day costs $3.73 of maintenance cost per mile per year. The corresponding figure for each additional light truck or passenger car per day is only 4¢ per mile per year. When an increase of 50 vehicles per day is assumed, the costs due to the two types of traffic compare as $183.10 vs. $2.18 with the marginal cost increase of the light truck or passenger car less than one-ninetieth of that of the heavy truck.

Evaluation of the Average Maintenance Cost of Heavy Truck Traffic

The average cost of heavy truck traffic can be evaluated as the increase in maintenance cost due to heavy truck traffic, divided by the heavy truck traffic volume. Table 6 summarizes the results of calculation, carried out for the same hypothetical average highway section as in Table 5. The table confirms the result obtained in Table 5 using the concept of marginal maintenance cost that the impact on highway maintenance cost of a heavy truck is approximately 90 times as much as that of a passenger car. The study results thus establishes the impact of heavy truck traffic upon pavement maintenance costs relative to that of light truck or passenger car traffic.

MAJOR CONCLUSIONS

The objective of this study has been to determine the factors which influence pavement maintenance costs for California state highways. In particular, it was desired that the impact of heavy truck traffic on maintenance cost be evaluated. To this end, over 1,000 one-mile sections of state highways were randomly sampled, and data from various sources were integrated for these sections to form as comprehensive a data set as possible. The variables included in the resulting data file represent traffic data, weather data, geometric data, and pavement maintenance cost data.

Following an extensive explorative analysis of the data, and after examining many alternative model formulations, a statistical model of pavement maintenance cost was formulated. The most important finding is that heavy truck traffic has much larger impact on pavement maintenance cost than does light truck or passenger car traffic. Our estimation results indicate, on a typical roadway, the average maintenance cost per heavy truck (five or more axles) is $7.60 per mile per year, while the cost per passenger car is approximately 8¢ per mile per year. It was further shown that one additional heavy truck per day would cost annually additional $3.73 for pavement maintenance per mile of a roadway. An increase by 50 heavy trucks would cost an additional $183.10 per year per mile. The corresponding cost increases due to light truck or passenger car traffic are 4¢ and $2.18 per year per mile, respectively. This study thus establishes that one heavy truck is approximately equivalent to 90 light trucks or passenger cars in terms of their impact on pavement maintenance costs.

In addition, the model indicates that the effect of weather on pavement maintenance costs is relatively small, with maintenance cost decreasing with the average annual temperature. The model also indicates, other things being equal, fewer funds are spent per mile on pavement maintenance in mountain areas.

As expected, maintenance cost increases with the age of the pavement. The study found, however, that this increase is small, presumably because routine pavement maintenance is performed at a certain rate regardless of the age of pavements. Substantial differences exist in per-mile maintenance costs across districts. District 2 is mostly rural, mountainous, and remote while District 11 includes San Diego County plus low elevation, hot and remote desert. The uniqueness of these districts include remoteness, mountains or desert and interstate highways. Perhaps these features combine to cause the significance for these district indicators. It was also found that less maintenance costs tend to be expended on minor collectors and on bridge sections.

This study has shown that a statistical analysis of carefully compiled data set is capable of providing useful information for pavement maintenance cost allocation. The robustness of the findings and the accuracy of the cost estimates will improve if the quality of the data can be improved. In particular, it is recommended that the definition of pavement age and the practice of cost proration be critically examined, and subgrade soil types and drainage conditions be introduced into the data base in the future.

MAJOR RECOMMENDATIONS

Extending the conclusions one can arrive at three major recommendations. First, the State of California should review its highway taxation policies. Second, effort should be directed to refine and improve this analysis and results contained herein. Finally, a national study should be taken to evaluate the applicability of this approach for other states. The following comments elaborate on these major recommendations.

While this study suggested a pavement maintenance cost distribution between heavy trucks and light vehicles on the order of one hundred times, the most recent California cost allocation effort [8] used a ratio of approximately two to one. This information of course implies a need for the State of California to review and perhaps revise current vehicle fee structure. There is a major policy issue totally separate from this research effort. The trucking industry provides benefit to our general economy which should be considered in the deliberations regarding vehicle fees.

As this research project neared completion several significant issues surfaced which were beyond the project's scope of work. An additional contract was recommended (and is now underway) to address the following concerns:

- variation in costs among districts,
- additional analysis of environmental effects,
- develop models with ESAL as an independent variable and
- develop separate models for rigid and flexible pavements.

The final major recommendation is for the development of national research project to 1) apply this approach to other states, and 2) prepare a supplement to the FHWA highway cost allocations guide dealing with pavement maintenance costs. The scope development of such a project should include discussion with appropriate AASHTO and TRB representatives as well as the FHWA.

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Table 1
The Number of Sample Sections by County

Alameda	27	Monterey	20	Trinity	12
Alpine	2	Napa	8	Tulare	26
Amador	9	Nevada	7	Tuolumne	6
Butte	5	Orange	29	Ventura	24
Calaveras	7	Placer	13	Yolo	16
Colusa	7	Plumas	14	Yuba	6
Contra Costa	12	Riverside	45		
Del Norte	7	San Bernardino	71		
El Dorado	14	Sacramento	21		
Fresno	33	San Diego	48		
Glenn	8	San Francisco	10		
Humboldt	23	San Luis Obispo	26		
Imperial	23	San Joaquin	22		
Inyo	19	San Mateo	20		
Kern	57	Santa Barbara	29		
Kings	12	Shasta	23		
Lake	11	San Benito	7		
Lassen	15	Santa Cruz	10		
Los Angeles	102	Sierra	4		
Madera	11	Siskiyou	24		
Marin	7	Santa Clara	26		
Mariposa	9	Solano	19		
Mendocino	25	Sonoma	20		
Merced	19	Sutter	8		
Modoc	11	Stanislaus	11		
Mono	24	Tehema	15		

Table 2
Variables Considered in the Development of
Pavement Cost Allocation Models

Variable	Description
Traffic	
HT-AADT	Heavy truck (5 or more axles) average annual daily traffic
P&LAADT	Passenger car and light truck average annual daily traffic
Roadway Geometry	
NLANES	Number of lanes in one direction
SHOULDER	Shoulder width (in feet)
NOSHOULDER	2.718 if the segment has no shoulder; 1 otherwise
WIDTH	Traveled way width in one direction (in feet)
District	
DISTRICTi	2.718 if the roadway segment lies in Caltrans District i (i is 1 through 11; 1 otherwise
Climate	
RAINFALL	Annual precipitation (in inches)
AATEMP	Average annual temperature (° F)
DECTEMP	Average December temperature (° F)
HTEMP	The highest temperature (° F)
ELEVATION	Elevation of the roadway segment (in feet)
MARITIME	2.718 if the roadway segment lies in the maritime climate; 1 otherwise
MOUNTAIN	2.718 is the roadway segment lies in the mountain climate; 1 otherwise
DESERT	2.718 if the roadway segment lies in the desert climate; 1 otherwise
VALLEY	2.718 if the roadway segment lies in the valley climate; 1 otherwise
Surface Type and Age	
RIGID	2.718 if the entire roadway segment has rigid pavements; 1 otherwise
FLEXIBLE	2.718 if the entire roadway segment has flexible; 1 otherwise
BRIDGE	2.718 if the entire roadway segment is a bridge; 1 otherwise
AGE	Pavement age (in years since last major pavement work)
Functional Classification	
PART-PART	Principal arterial connecting to principal arterial
PART-MART	Principal arterial connecting to minor arterial
PARTCART	Principal arterial, no connecting link
MINORART	Minor arterial
MJCOLLCTR	Major collector
MNCOLLCTR	Minor collector
TOTALCOST	Total 1984-87 pavement maintenance cost (in dollars)

Table 3
Descriptive Statistics of the Variables in the Data Files of the Study

Variable	N	Mean	Standard Deviation	Minimum	Maximum
HT-AADT	1119	987.5	1784.0	0	18250
P&LAADT(x 10^3)	1119	23.7	38.4	0	259.8
ELEVATION	1082	1157.5	1718.4	-119	9120
NLANES	1119	1.69	.92	1	6
WIDTH	1119	20.4	11.5	8	84
RAINFALL	1082	19.1	12.3	2.6	74.9
SHOULDER	1119	6.61	3.52	0	21
AATEMP	1082	58.99	6.01	39.2	73.3
DECTEMP	1081	47.17	6.69	26	57.4
AGE	1119	18.40	6.05	1	23
TOTALCOST(x 10^3)	1119	89.1	119.8	0	810.2

Climate Type	N
MARITIME	322
MOUNTAIN	188
DESERT	64
VALLEY	500
Total	1074

Surface Type	N
RIGID	100
FLEXIBLE	528
BRIDGE	45
MIXED	446
Total	1119

District	N
1	64
2	115
3	113
4	136
5	76
6	126
7	145
8	103
9	55
10	104
11	82
Total	1119

Functional Class	N
PART-TIME	415
PART-MART	104
PARTCART	121
MINORART	391
MJCOLLCTR	69
MNCOLLCTR	9
Total	1109

Table 4
Multiplicative Model of Pavement Maintenance Cost

	β	t
Constant	17.66	
ln (HT-AADT)	0.21	5.58
ln(P&LAADT)	0.06	1.13
ln(AGE)	0.17	1.80
ln(SHOULDER)	-0.36	-3.16
NOSHOULDER	-0.61	-2.06
ln(AATEMP)	-2.11	-2.84
MOUNTAIN	-0.38	-1.81
BRIDGE	-1.49	-2.68
MNCOLLCTR	-1.23	-1.73
DISTRICT2	0.66	2.93
DISTRICT11	0.60	2.85
F	8.63	
df	(11,995)	
R^2	0.09	
N	1007	

Note: Excludes sections with zero maintenance costs.

β = regression coefficient
t = t-statistics (critical value = 1.96 at α = 5%)
F = F-statistics (critical value = 1.80 at α = 5%)
df = degrees of freedom
R^2 = coefficient of determination
N = sample size

Table 5
Marginal Increase in Pavement Maintenance Cost
Due to Additional Traffic

Heavy Truck		Passenger Car & Light Truck	
Increase in Traffic	Increase in Maintenance Cost	Increase in Traffic	Increase in Maintenance Cost
1	3.73	1	0.04
5	18.64	5	0.22
10	37.20	10	0.44
25	92.45	25	1.09
50	183.10	50	2.18
(Vehicles/day)	($/year/mi)	(vehicles/day)	($/year/mi)

Note: The marginal cost increases are evaluated for a roadway section which is not in the mountain climate, not a bridge section, not a minor collector, and is not in District 2 or 11. The sample average values are used for HT-AADT, P&LAADT, AGE, SHOULDER, and AATEMP (see Table 3 for the values used).

Table 6
Average Maintenance Cost per Vehicle

Heavy Truck Volume	Heavy Truck Cost/vehicle	Passenger Car & Light Truck Volume	Passenger Car & Light Truck Cost/Vehicle
250	20.44	5000	0.31
500	12.53	15000	0.12
987.5 *	7.67	23700 *	0.08
1000	7.60	25000	0.08
2000	4.57	50000	0.04
5000	2.31	100000	0.02
Vehicles/day	$/year/mile	Vehicles/day	$/year/mile

*Sample mean traffic volume.

NOTE: Maintenance costs are calculated assuming average roadway and climatic conditions (see the note in Table 5) using the following formula:

$$\text{Average Cost} = \frac{\text{Total Cost - Fixed Cost}}{\text{Traffic Volume}}$$

where the fixed cost is obtained assuming no traffic.