BENEFIT ANALYSIS FOR PAVEMENT DESIGN SYSTEMS

By

William F. McFarland

Research Report Number 123-13

A System Analysis of Pavement Design and Research Implementation

Research Project 1-8-69-123

conducted

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration
Bureau of Public Roads

by the

Highway Design Division Research Section
Texas Highway Department

Texas Transportation Institute
Texas A&M University

Center for Highway Research
The University of Texas at Austin

April, 1972

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PREFACE

This report presents a model for relating motorist benefits to pavement quality as measured by the pavement serviceability index, and motorist benefits are estimated using several assumptions. The report also includes a discussion of different methods of economic analysis that can be used to compare pavement design strategies.

The report is one of a series issued under Research Study 1-8-69-123, "A Systems Analysis of Pavement Design and Research Implementation." This study is being conducted jointly by principal investigators and their staffs in three agencies--The Texas Highway Department, The Center for Highway Research, and The Texas Transportation Institute--as a part of the cooperative research program with the Department of Transportation, Federal Highway Administration.

The contents of this report reflect the views of the author who is 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 Federal Highway Administration. This report does not constitute a standard, specification or regulation.

William F. McFarland

LIST OF REPORTS

Report No. 123-1, "A Systems Approach Applied to Pavement Design and Research," by W. Ronald Hudson, B. Frank McCullough, F. H. Scrivner, and James L. Brown, describes a long-range comprehensive research program to develop a pavement systems analysis and presents a working systems model for the design of flexible pavements.

Report No. 123-2, "A Recommended Texas Highway Department Pavement Design System Users Manual," by James L. Brown, Larry J. Buttler, and Hugo E. Orellana, is a manual of instructions to Texas Highway Department personnel for obtaining and processing data for flexible pavement design system.

Report No. 123-3, "Characterization of the Swelling Clay Parameter Used in the Pavement Design System," by Arthur W. Witt, III, and B. Frank McCullough, describes the results of a study of the swelling clay parameter used in pavement design system.

Report No. 123-4, "Developing a Pavement Feedback Data System," by R. C. G. Haas, describes the initial planning and development of a pavement feedback data system.

Report No. 123-5, "A Systems Analysis of Rigid Pavement Design," by Ramesh K. Kher, W. R. Hudson, and B. F. McCullough, describes the development of a working systems model for the design of rigid pavements.

Report No. 123-6, "Calculation of the Elastic Moduli of a Two-Layer Pavement System from Measured Surface Deflections," by F. H. Scrivner, C. H. Michalak, and W. M. Moore, describes a computer program which will serve as a subsystem of a future Flexible Pavement System founded on linear elastic theory.

Report No. 123-6A, "Calculation of the Elastic Moduli of a Two-Layer Pavement System from Measured Surface Deflections, Part II," is a supplement to Report 123-6, prepared by the same authors.

Report No. 123-7, "Annual Report on Important 1970-71 Pavement Research Needs," by B. Frank McCullough, James L. Brown, W. Ronald Hudson, and F. H. Scrivner, describes a list of priority research items based on findings from use of the pavement design system.

Report No. 123-8, "A Sensitivity Analysis of Flexible Pavement System FPS2," by Ramesh K. Kher, B. Frank McCullough, and W. Ronald Hudson, describes the overall importance of this system, the relative importance of the variables of the system and recommendations for efficient use of the computer program.

Report No. 123-9, "Skid Resistance Considerations in the Flexible Pavement Design System," by David C. Steitle and B. Frank McCullough, describes skid resistance consideration in the Flexible Pavement System based on the testing of aggregates in the laboratory to predict field performance and presents nomograph for the field engineer to use to eliminate aggregates which would not provide adequate skid resistance performance.

Report No. 123-10, "Flexible Pavement System - Second Generation, Incorporating Fatigue and Stochastic Concepts," by Surendra Prakash Jain, B. Frank McCullough, and W. Ronald Hudson, describes the development of new structural design models for the design of flexible pavement which will replace the empirical relationship used at present in flexible pavement systems to simulate the transformation between the input variables and performance of a pavement.

Report No. 123-11, "Flexible Pavement System Computer Program Documentation," by Dale L. Schafer, provides a documentation of the FPS-9 computer program.

Report No. 123-12, "A Pavement Feedback Data System," by Oren G. Strom, provides recommendations and requirements for a pavement feedback data system for Texas.

Report No. 123-13, "Benefit Analysis for Pavement Design Systems," by William F. McFarland, describes a method for relating motorist benefits to the serviceability index.

ABSTRACT

The Texas Pavement Design System of the Texas Highway Department includes computer programs that compare pavement design strategies on the basis of effectiveness and cost. The effectiveness of pavements is measured primarily by the pavement serviceability index. This report presents the results of an investigation to determine the possibility of relating motorist benefits to the pavement serviceability index and of using these benefits in the comparison of pavement design strategies. The motorist benefits that are considered are those associated with travel time, vehicle operating costs, accident costs, and discomfort. A model for relating motorist benefits to the pavement serviceability index is presented and preliminary estimates of benefits are developed.

KEY WORDS: Pavements, pavement design, systems analysis, optimization, cost-effectiveness analysis, benefit-cost analysis, pavement economics, pavement benefits, user costs, Texas Highway Department.

SUMMARY

This report presents a model for relating motorist benefits to the pavement serviceability index and also explains how different methods of economic analysis can be used to compare pavement design strategies using these benefit estimates together with pavement costs. The motorist benefits that are considered are reductions in motorist (or user) costs that result from higher levels of the pavement serviceability index. The four types of user costs that are considered are those associated with travel time, vehicle operation, accidents, and discomfort.

User costs are estimated for six different types of roads, three urban and three rural. In general, the model for estimating user costs consists of two steps. First, each type of user cost is estimated as a function of speed for different levels of the pavement serviceability index. Second, actual speeds are assumed for different types of roads at each level of the serviceability index; these assumed actual speeds are used to estimate the actual user costs for each specific situation that is considered. It should be emphasized that because of the lack of needed data on user costs as related to the pavement serviceability index, further research is needed before the benefit model can be used with confidence. However, the model for estimating user costs appears promising and indicates some of the future research that is needed to improve the user cost estimates. Also, sensitivity analyses employing the user cost estimates in the report should yield interesting results.

In addition to providing a model for relating user costs to the pavement serviceability index and developing preliminary estimates of these user costs,

the report also includes a discussion and comparison of different methods of economic analysis that can be used to compare pavement designs. It is concluded that the benefit-cost method appears to be the method that is best suited for comparing pavement designs, if accurate estimates of benefits can be derived.

IMPLEMENTATION STATEMENT

This report presents a model for relating motorist benefits to the pavement serviceability index. There are two principal ways in which the information in the report can be used. First, the benefit data that are developed can be used in sensitivity analyses to give a general indication of how the optimum minimum allowable pavement serviceability index changes in relation to changes in pavement design variables. Second, the overall model presented for estimating benefits provides guidelines regarding future research that is needed for improving the estimates of motorists' benefits associated with pavement quality.

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CHAPTER 1

INTRODUCTION

The purpose of this report is to present a model for relating motorist benefits to the pavement serviceability index and to explain how different methods of economic analysis can be used to compare pavement design strategies using these benefit estimates together with pavement costs. The motorist benefits that are considered are reductions in motorist (or user) costs that result from higher levels of the pavement serviceability index. The four types of user costs that are considered in detail are those associated with travel time, vehicle operation, accidents, and discomfort.

These four types of costs are estimated for six different types of roads, three urban and three rural. In general the model for estimating user costs consists of two steps. First, each type of cost is estimated as a function of vehicle speed for different levels of the pavement serviceability index. Second, given estimates of the actual operating speeds on different types of roads at each level of the pavement serviceability index, estimates of the actual user costs for each specific situation are derived.

It should be emphasized that because of the lack of needed data on user costs as related to the pavement serviceability index, the specific user cost estimates derived in this report cannot be used with confidence to estimate benefits for use in benefit-cost analysis. However, the model does provide a guide to needed future research and also can be used in sensitivity analyses.

The plan of the report is as follows. Chapter 2 gives the results of a state-of-the-art review of attempts to relate motorists' economic benefits to the pavement serviceability. In Chapter 2, the emphasis is on using the relevant literature, rather than simply documenting its existence. Since existing literature does not relate motorists' benefits to the pavement serviceability index, these relationships are assumed, using existing literature as a guide. The overall benefit model presented in Chapter 2 consists of four specific benefit models, relating to time costs, vehicle operating costs, accident costs, and discomfort costs. The costs of air and noise pollution are not estimated but are briefly discussed in Appendix A.

Chapter 3 presents a review of different economic methods of analysis that can be used to compare alternative pavement designs. The methods that are explained and compared are the cost-effectiveness method, the cost-of-time method, the benefit-cost method, the rate-of-return method, and the total-transportation-cost method.

In Chapter 4, the cost-effectiveness method of analysis currently used in the computer programs of the Texas Pavement Design System is explained. The two principal ways in which benefit estimates can be included in the present system are explained.

Chapter 5 gives a discussion of some of the limitations of the benefit model and data and tells how the model might best be improved in future research.

CHAPTER 2

BENEFIT MEASUREMENT AND PAVEMENT SERVICEABILITY

2.1 RELATING USER COSTS TO THE PAVEMENT SERVICEABILITY

This chapter presents an attempt to measure the relationship between user costs and pavement serviceability. The objective is to determine how user costs might be expected to change as the pavement serviceability index changes over the life of a pavement.

In general, user costs are a function of many variables, associated with characteristics of the roadway, vehicles, drivers, and the environment. The basic question asked here is, given all other characteristics of a situation, how do user costs change with pavement quality as measured by the serviceability index? In posing this question, it is implicitly assumed that pavement serviceability is a good measure of overall pavement quality. It is recognized, however, that a more comprehensive study should focus attention on all aspects of pavement quality (as they relate to the highway user) and not merely on pavement serviceability. Measures of pavement quality other than the pavement serviceability index might be the pavement's coefficient of friction, its reflectability, its color, etc. The difficulty of considering several measures of pavement quality is compounded by the fact that these measures are affected by other non-pavement-associated variables. In this study, attention is focused on the pavement serviceability index since this is the variable currently being used as the measure of effectiveness in the Texas Pavement Design System.

The user costs considered in the following discussion are (1) travel time costs, (2) vehicle operating costs, (3) accident costs, and (4) discomfort costs. An attempt is made to relate each of these user costs to the pavement serviceability index. Then, given the expected traffic and the expected serviceability index each as a function of time, over the analysis period, it is possible to estimate total user costs for a given pavement during the analysis period that is being considered.

It should be mentioned at the outset that no concerted attempt has ever been made to relate user costs or benefits to pavement serviceability. The present attempt is limited considerably by the lack of basic research in this field. Therefore, the present study in some ways may be viewed as providing a model for determining research needs instead of providing definitive answers to the problems posed. Nevertheless, through the use of broad assumptions, the study does provide a relationship between the stated user costs and the serviceability index.

2.2 PAVEMENT SERVICEABILITY AND VEHICLE SPEEDS

After a pavement is built initially or resurfaced, it has a certain serviceability index. This pavement serviceability index decreases over time until it reaches a level at which it is no longer acceptable and the pavement is overlayed (or has seal coat maintenance work performed on it). Figure 1 shows how the pavement serviceability index is assumed to change over time. In the Texas Pavement Design System, this drop in the serviceability index over time is determined by the number of 18-kip axle equivalents traveling on the road and by the amount of swelling due to expandable clays. (During any period before a pavement overlay occurs, normal routine maintenance, which has a minor effect on serviceability, is performed and this is assumed to be shown in the curve.) In the absence of seal coats, it might be expected that the coefficient of friction for a given pavement also would behave in a manner similar to that shown for the serviceability index, though the decrease would not necessarily be proportionate, nor a function of exactly the same variables, of course.

As the pavement serviceability index drops over time, the vehicles that use the pavement decrease their speeds to adjust for the reduced serviceability. This is because the "optimum" speed of travel of persons using a roadway is lower the lower is the serviceability index. This relationship is depicted in a general sense in Figure 2, which shows two hypothetical total user cost curves (each relating total user costs per vehicle mile to vehicle speed), one for a serviceability index of 3.0 and the other for 4.0. Here, total user costs are assumed to include <u>any</u> user costs perceived by the motorist under consideration, and the motorist, acting rationally, is assumed to travel at that speed that minimizes his total user costs in the given situation. The time cost portion of total user costs would be exactly the same for

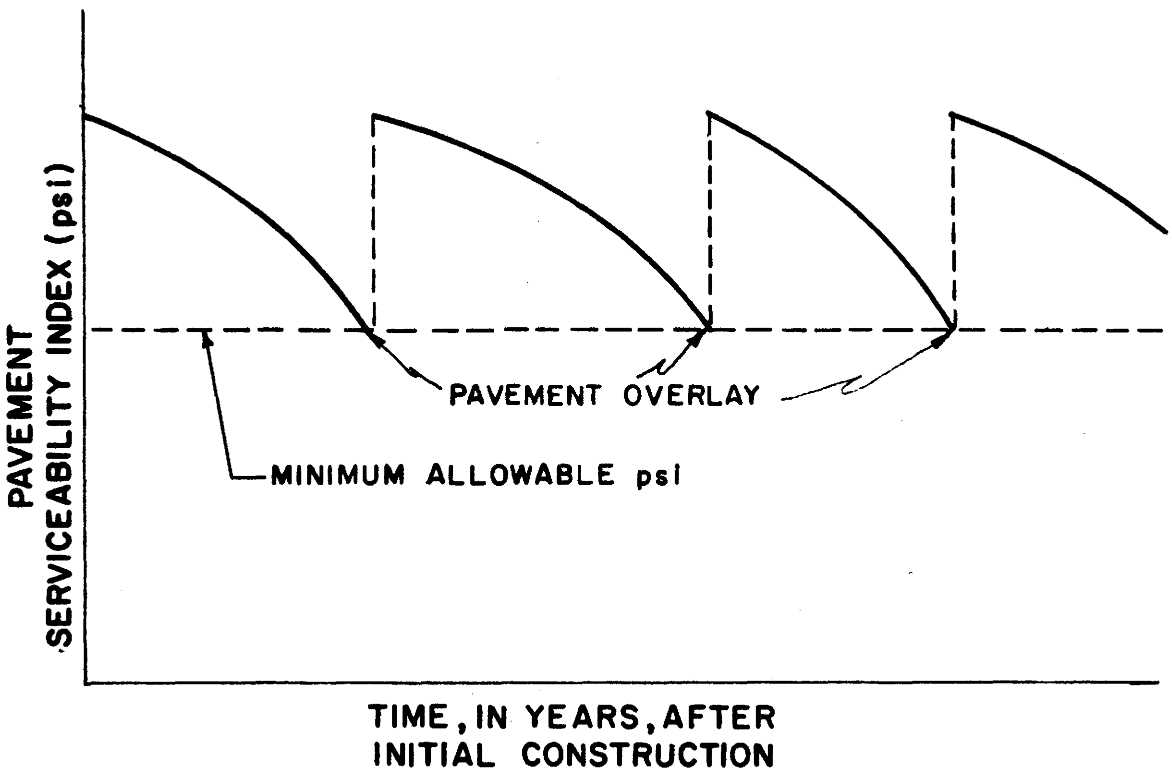

Figure 1: Pavement serviceability index related to time after initial construction.

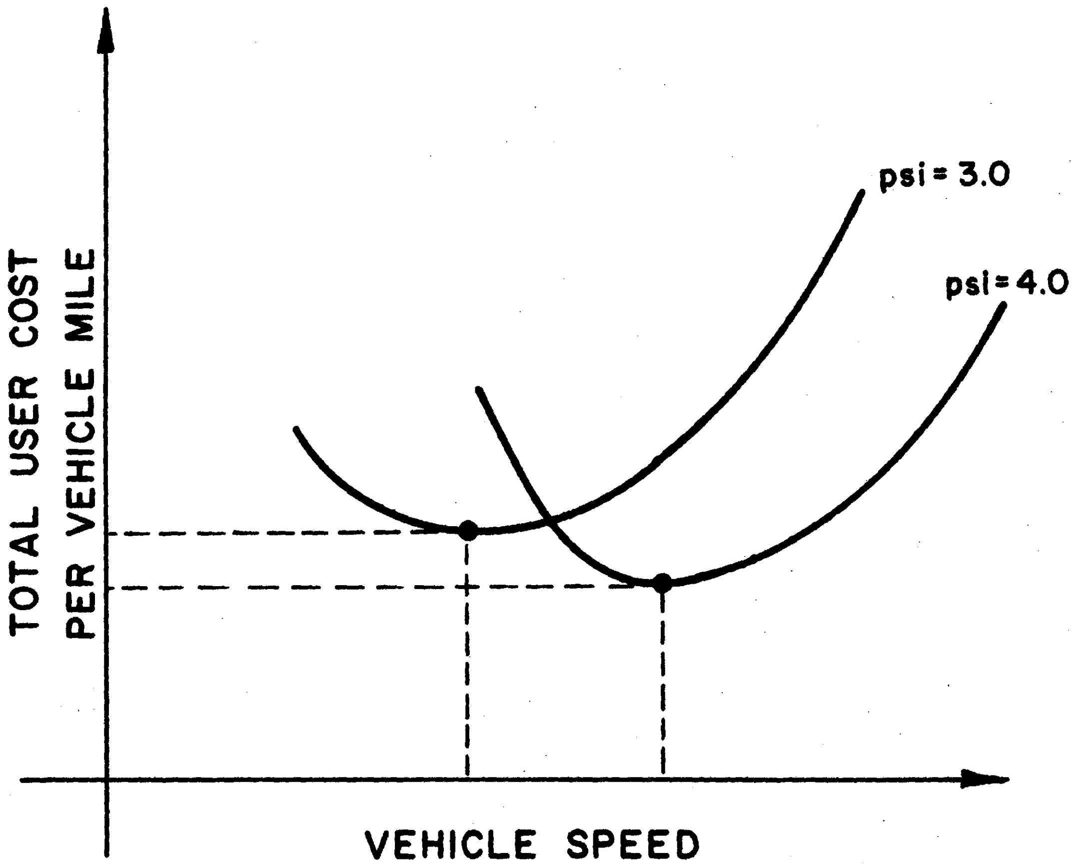

Figure 2: Total user costs related to vehicle speed and pavement serviceability index.

each serviceability index, but the other costs (including, it might be assumed, vehicle operating cost, accident cost, discomfort cost, and possibly other costs) are larger for the lower serviceability index. Thus, the "optimum" speeds, using this implied definition of optimum, are the actual speeds observed on any given roadway. These speeds are expected to vary as do people's tastes or desires, their vehicles, and other factors, including the way in which people perceive their costs (as opposed, say, to what their actual costs are).

Knowledge regarding the actual speeds that people drive in situations with different characteristics, including pavement characteristics, is extremely important in any study that attempts to relate user costs to pavement serviceability for at least two reasons. First, the vehicle speed is one of the two inputs used for measuring time costs per vehicle mile, the other input being time cost per vehicle per unit of time. Second, since test vehicle data usually are used to estimate vehicle operating costs, and since these data usually are related not only to pavement type but also to vehicle speed, vehicle speed is needed for estimating vehicle operating costs.

Unfortunately, the literature survey did not reveal any studies that attempted to relate vehicle speeds to the pavement serviceability index. One English study [27], however, did estimate the increase in spot speeds at one site where the pavement was resurfaced in a routine maintenance program. The one site for which data were given showed the following increases in speed:

Private Autos	+	4.8 mph
Light Commercial	+	3.5 mph
Medium Commercial	+	2.4 mph
Heavy Commercial	+	1.5 mph

In this study it is assumed that the average spot speeds for each level of the serviceability index between 1.5 and 5.0 are as given in Figure 3 and Table 1. It might be noted that the average spot speeds are assumed to decrease at an increasing rate as the lower levels of the serviceability index are reached. Also note that the increase in speeds is assumed to be five miles per hour between a serviceability index of 3.0 and 4.5, which is about the same as the change shown for resurfacing in the English study previously mentioned, assuming the usual high proportion of passenger cars.

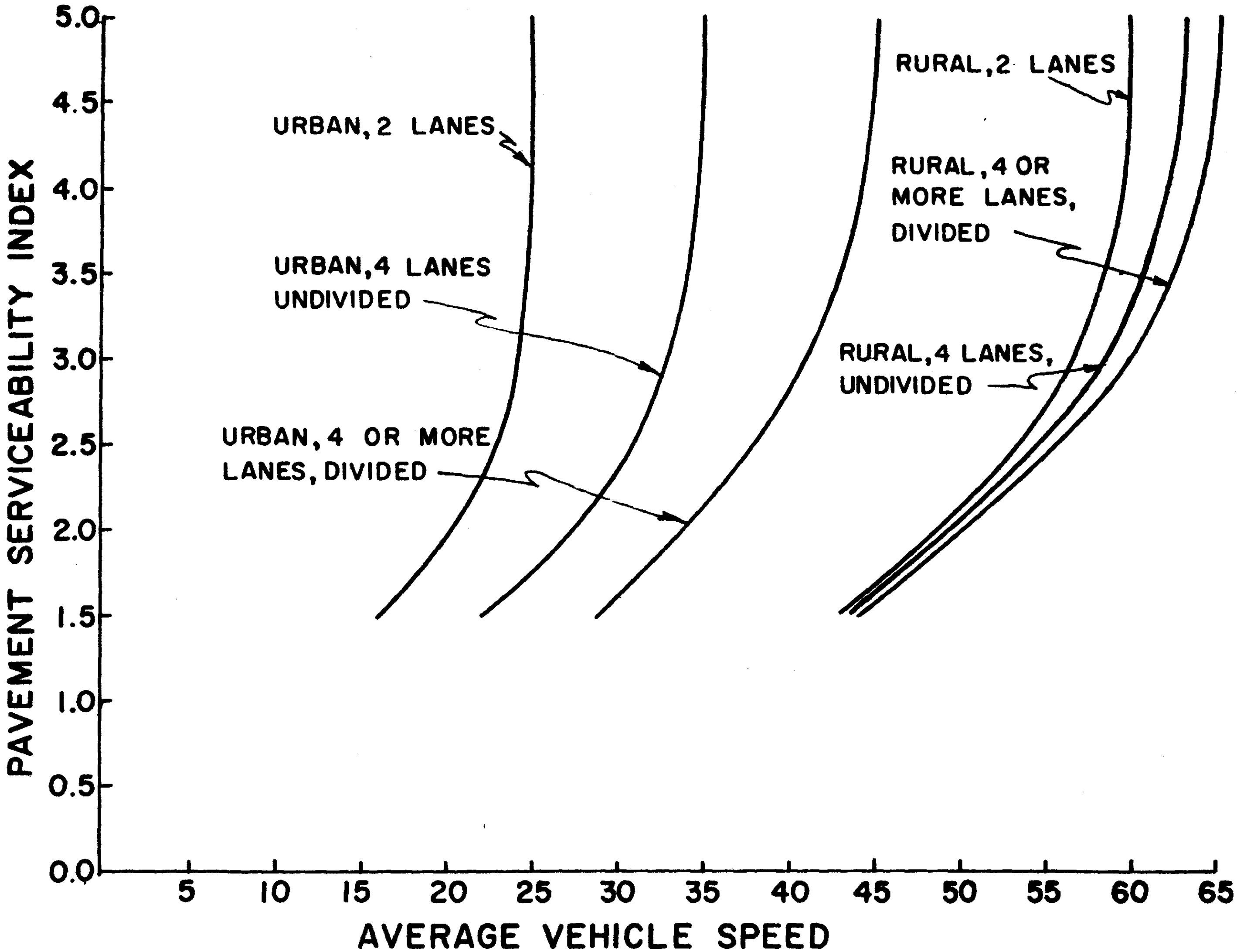

Figure 3: Average vehicle speed related to pavement serviceability index by type of road.

Table 1.

AVERAGE VEHICLE SPEEDS RELATED TO SERVICEABILITY INDEX, BY TYPE OF AREA AND TYPE OF ROAD

Pavement Serviceability Index	Average Vehicle Speed (mph) by Type of Area and Type of Road					
	Urban			Rural		
	2-lane	4-lane, undivided	4 or more lanes, divided	2-lane	4-lane, undivided	4 or more lanes, divided
1.5	16.0	22.0	29.0	43.0	43.5	44.0
2.0	20.0	27.0	34.0	48.5	49.5	50.0
2.5	23.0	31.0	38.0	53.5	54.5	55.5
3.0	24.0	33.0	41.0	56.5	58.5	60.0
3.5	25.0	34.0	43.0	58.5	60.5	62.5
4.0	25.0	34.5	44.0	59.5	62.0	64.0
4.5	25.0	35.0	45.0	60.0	63.0	65.0
5.0	25.0	35.0	45.0	60.0	63.0	65.0

2.3 TRAVEL TIME COSTS

Given the average travel speeds from Table 1, the only additional information needed for developing travel time costs per vehicle mile are the travel time costs (or values) per vehicle hour.

Numerous studies have evaluated the dollar value of time savings. Several researchers have studied situations for which there were two similar roads one of which was a toll road on which travel times were less than on the other road. In addition, many of the toll roads required less stops, had lower accident rates, and required less fuel consumption (compared to fuel consumption at the same average speed on the other road). These researchers argued that the amount consumers paid in tolls less their savings in operating costs and accident costs represented how much they paid for time savings [7, 19, 31, 34].

Besides using this toll-road method researchers have calculated the value of time savings: (1) by determining the extra vehicle operating cost motorists are willing to incur, either by traveling at high speeds or by taking alternate routes, to save time, [28, 33] (2) by determining the extra cost for faster modes of travel, e.g., air versus rail and car versus bus [3] (3) by determining how much extra cost for a residence motorists are willing to pay to locate so as to reduce their travel times [22], and (4) by determining the relation between work time, travel time, and leisure time, and then saying what the value of saving an hour of travel time appears to be [4].

Among the more recent studies evaluating the dollar value of time, there are five of particular importance, three dealing with the value of time for passenger cars [12, 20] and two dealing with the value of time for commercial vehicles [1, 13]. Recent values of time per person per hour for passenger car occupants are approximately $3.00 and values of time per vehicle per hour for commercial vehicles are approximately $6.00. One important fact that is mentioned in several of these studies is that very small increments of time savings may not have as high values per unit as do larger time savings increments.

Weighted average values of time per vehicle hour were developed previously from the above studies and these values (after updating for inflation) are currently used in the Texas Pavement Design System. These values are $3.96 per vehicle hour for urban areas and $4.24 per vehicle hour for rural areas. Using these values with the average speeds from Table 1, costs per vehicle mile for different types of roads and different pavement serviceability indices were developed and are given in Table 2.

Table 2.

TRAVEL TIME COSTS, IN CENTS PER VEHICLE MILE, RELATED TO SERVICEABILITY INDEX, BY TYPE OF AREA AND TYPE OF ROAD

Pavement Serviceability Index	Travel Time Costs, in Cents per Vehicle Mile, by Type of Area and Type of Road					
	Urban			Rural		
	2-lane	4-lane, undivided	4 or more lanes, divided	2-lane	4-lane, undivided	4 or more lanes, divided
1.5	24.74	18.00	13.66	9.86	9.75	9.64
2.0	19.80	14.67	11.65	8.74	8.57	8.48
2.5	17.22	12.77	10.42	7.93	7.78	7.65
3.0	16.50	12.00	9.66	7.50	7.25	7.07
3.5	15.84	11.65	9.21	7.25	7.01	6.78
4.0	15.84	11.48	9.00	7.13	6.84	6.63
4.5	15.84	11.31	8.80	7.07	6.73	6.52
5.0	15.84	11.31	8.80	7.07	6.73	6.52

2.4 VEHICLE OPERATING COSTS

The vehicle operating costs that are considered in this section include the costs of fuel, tires, oil, maintenance, and depreciation. The major factors that affect vehicle operating costs, according to the Red Book [2], are: the type of vehicle; the type design and location of the road; the amount of traffic; and the speed of the vehicle.

Although numerous vehicle operating cost studies have been made using different vehicles in different situations, there has been no study that attempted to relate vehicle operating costs to the pavement serviceability index or any similar measure of pavement quality. Several studies have calculated costs for different types of surfaces - usually paved surface, gravel surface, and unsurfaced (or earth surface).

The Red Book [2] presents passenger car operating costs for paved, gravel, and earth surfaces, although a full range of speeds is not covered. The Red Book costs are shown in Table 3 for a speed of 36 miles per hour. Table 4 shows the ratios of these costs relative to the paved surface.

Bonney and Stevens [5] present information on the relative costs of operating commercial vehicles on paved, gravel, and earth surfaces, and their relative costs are presented in Table 5. It should be noted that these costs are for vehicles in regular service and, therefore, the costs are not for the same speeds on each surface. Thus, the principal reason the fuel costs on gravel and earth surfaces are not considerably above those on paved surfaces probably is because the average operating speeds were higher on paved surfaces.

The most recent study on vehicle operating costs was done by Claffey [8], who developed fuel costs for four vehicle types operating on

TABLE 3

PASSENGER CAR OPERATING COSTS AT A SPEED OF 36 MILES PER HOUR, BY TYPE OF COST AND TYPE OF SURFACE

Type of Cost	Cost in Cents Per Vehicle Mile by Type of Surface		
	Paved*	Gravel	Earth
Fuel	1.91	2.21	2.79
Tires	0.26	0.75	1.07
Oil	0.15	0.22	0.32
Maintenance and Repairs	1.20	1.80	2.40
Depreciation	1.50	1.50	1.50
Total	5.02	6.48	8.08

*Costs for paved surface are for "free operation" on a 2-lane road.

TABLE 4

RELATIVE COSTS OF PASSENGER CAR OPERATION
ON GRAVEL AND EARTH SURFACES
AS COMPARED TO OPERATION ON PAVED
SURFACES, FOR VEHICLE SPEED OF 36 MPH

Type of Cost	Ratio of Cost to Cost of Operating on Paved Surface		
	Paved	Gravel	Earth
Fuel	1.00	1.16	1.46
Tires	1.00	2.88	4.12
Oil	1.00	1.47	2.13
Maintenance and Repairs	1.00	1.50	2.00
Depreciation	1.00	1.00	1.00
Total*	1.00	1.41	1.87

* Omitting depreciation, which the Red Book assumes to be independent of type of surface.

TABLE 5

RELATIVE COSTS OF COMMERCIAL VEHICLE OPERATION ON GRAVEL AND EARTH SURFACES AS COMPARED TO OPERATION ON PAVED SURFACES

Type of Cost	Ratio of Cost to Cost of Operating on Paved Surface		
	Paved	Gravel	Earth
Fuel	1.0	1.0	1.2
Tires	1.0	1.1	1.5
Oil	1.0	1.0+	1.5
Maintenance	1.0	2.0	6.0

Note: These relative costs are for 65 commercial vehicles (46 buses and 19 trucks), operated in regular service.

four surface types. These relative fuel costs are shown in Table 6. Claffey also developed tire costs for two vehicle types and three surface types; these relative costs are presented in Table 7. Comparing Claffey fuel correction ratios for passenger cars with those of the Red Book at 36 miles per hour, it is noted that Claffey's ratio of fuel consumption on gravel compared to paved surfaces is about 1.40 (interpolated) whereas the analogous value from the Red Book is only 1.16. Claffey's fuel ratio of 1.40 at 36 mph on gravel is about the same as the Red Book's overall vehicle operating cost ratio on gravel, which is 1.41. The information from Bonney and Stevens is not comparable since it is for commercial vehicles operating at regular service speeds.

Claffey's study was the only study that compared fuel costs for operating on two different types of paved surfaces, some in good condition and some in very poor condition. The paved roads in good condition were high-type cement or asphalt pavements meeting Interstate standards, and the paved road in poor condition was a badly broken and patched asphalt pavement. Claffey's fuel correction factors for passenger cars from Table 6 are shown in Figure 4. The passenger car fuel costs at 50 mph on the badly broken and patched asphalt surface were about 1.5 times those for the roads meeting Interstate standards. Tire costs were not compared for these two types of roads. From the tire costs on gravel relative to the high-type paved surfaces, however, it appears that the tire cost multiplier would be even larger than that for fuel. Also, the correction factors given by the Red Book and Bonney and Stevens indicate that the correction factors for oil, maintenance, and depreciation would be higher than for fuel.

Table 6

Correction Factors For Adjusting

Vehicle Fuel Consumption

Vehicle Type and Uniform Speed (mph)	Correction Factors by Road Surface			
	High-Type Concrete or Asphalt	Badly Broken and Patched Asphalt	Dry Well-Packed Gravel	Loose Sand
Passenger Cars:				
10	1.00	1.01	1.09	1.23
20	1.00	1.05	1.13	1.28
30	1.00	1.20	1.26	1.40
40	1.00	1.34	1.56	1.73
50	1.00	1.50	1.70	2.00
Pickups:				
10	1.00	1.00	1.07	1.33
20	1.00	1.00	1.09	1.49
30	1.00	1.01	1.16	1.67
40	1.00	1.06	1.27	2.02
50	1.00	1.16	1.34	--
Two-Axle, Six-Tire Trucks:				
10	1.00	1.03	1.24	1.46
20	1.00	1.06	1.28	1.62
30	1.00	1.07	1.45	2.16
40	1.00	1.08	1.58	2.46
50	1.00	1.20	1.69	--
Tractor Semi-Trailers:				
10	1.00	--	1.07	--
20	1.00	--	1.27	--
30	1.00	--	1.59	--
40	1.00	--	1.75	--

Source: Ref. 8 , pp. 17, 22, 24, 27.

TABLE 7

CORRECTION FACTORS, RELATIVE TO HIGH TYPE ASPHALT, FOR TIRE COSTS

Vehicle Type and Uniform Speed (mph)	Correction Factors by Road Surface		
	High-Type Concrete	High-Type Asphalt	Dry Well-Packed Gravel
Passenger Car:			
20	.33	1.00	3.81
30	.53	1.00	2.92
40	.67	1.00	2.49
50	.71	1.00	2.44
60	.67	1.00	—
70	.68	1.00	--
80	.63	1.00	—
Pickup:			
20	.31	1.00	3.81
30	.52	1.00	2.95
40	.67	1.00	2.47
50	.72	1.00	2.45

Source: Ref. 8 , pp. 31, 33.

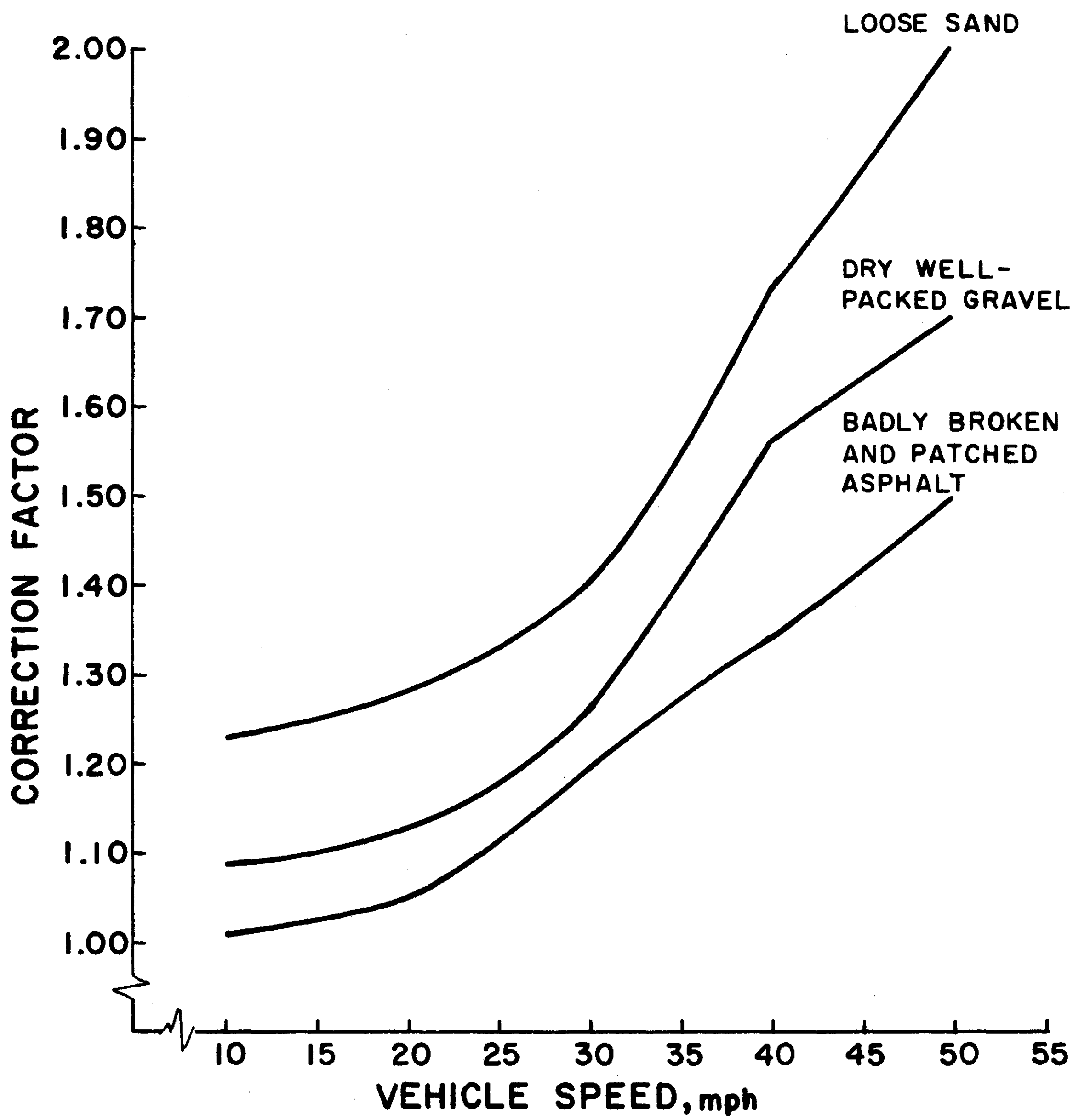

Figure 4: Passenger car fuel correction factors for different surface types relative to high type paved surface, by vehicle speed.

Another factor that needs to be considered is that Claffey's data were for test drivers and test vehicles operating at uniform speeds. The Red Book indicates that the costs for motorists and vehicles in normal operation would be about 25% higher than those for test drivers and test vehicles. This effect probably would be more pronounced the lower the pavement serviceability index because motorists probably would make more speed changes in relation to the pavement surface, instead of traveling at a constant, uniform speed like the test vehicles.

Overall, what is needed in the present study are correction factors for each operating cost and each type of vehicle operating at different average speeds on pavements with different serviceability indices. Since these comprehensive correction factors are not available, it was decided that overall correction factors (covering all operating costs for a composite, average vehicle) would be assumed. These assumed correction factors are shown in Figure 5. These correction factors are assumed to apply to the vehicle operating costs for both urban and rural areas that are currently used in the Texas Pavement Design System, with these currently-used costs being assumed to be applicable to a highway with a pavement serviceability index of 4.0. Therefore, the correction factor shown in Figure 5 for a pavement serviceability index of 4.0 is 1.0 at all speeds. The correction factors for other levels of the pavement serviceability index are assumed to increase at an increasing rate with respect to both higher speeds and lower levels of the pavement serviceability index. It might be noted that the correction factors for a pavement serviceability index of 1.5 are slightly larger than those that Claffey reported for fuel for passenger cars on badly patched and broken asphalt relative to high-type concrete or asphalt.

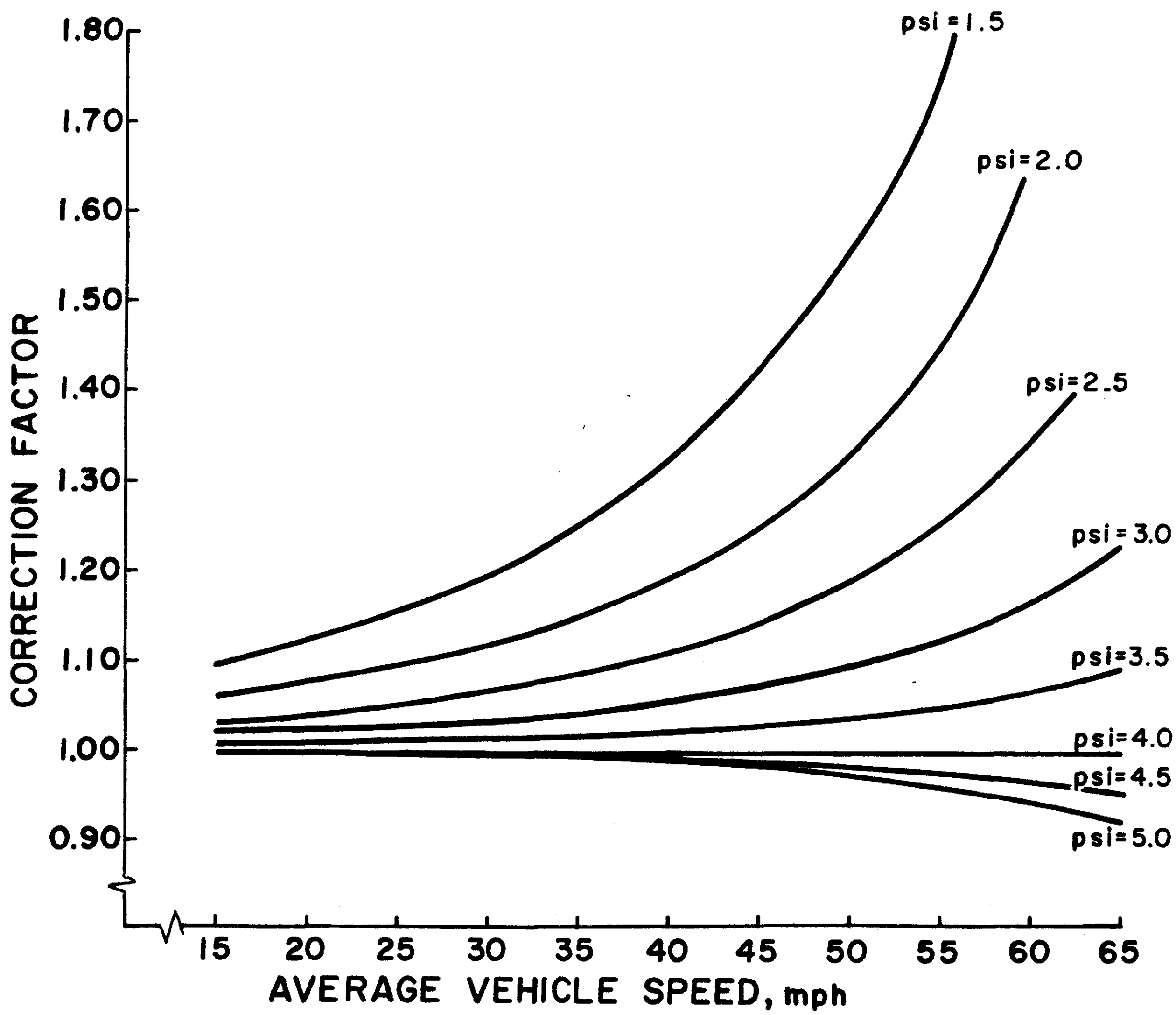

Figure 5: Composite vehicle operating cost correction factors for different pavement serviceability indexes, by average vehicle speed.

The correction factors from Figure 5 are also given in Table 8. These correction factors multiplied by the vehicle operating costs currently used in the Texas Pavement Design System give the vehicle operating costs for urban and rural areas shown in Tables 9 and 10. In Tables 9 and 10, the vehicle operating costs at a pavement serviceability index of 4.0 are the costs currently used in the Texas Pavement Design System, since the correction factor is 1.0 at all speeds for a pavement serviceability index of 4.0.

Using the average operating speeds on different types of roads with different serviceability indices from Table 1 with the vehicle operating costs from Tables 9 and 10, the vehicle operating costs at actual operating speeds can be derived for different types of roads at each level of the serviceability index. These vehicle operating costs are shown in Table 11. These operating costs from Tables 9, 10, and 11 are also shown in Figures 6 and 7.

TABLE 8

VEHICLE OPERATING COST CORRECTION FACTORS FOR COMPOSITE VEHICLE, BY AVERAGE VEHICLE SPEED AND LEVEL OF PAVEMENT SERVICEABILITY INDEX

Average	Pavement Serviceability Index							
Speed, mph	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
15	1.100	1.060	1.033	1.017	1.007	1.000	1.000	1.000
20	1.125	1.075	1.042	1.021	1.008	1.000	.999	.998
25	1.155	1.093	1.052	1.026	1.010	1.000	.998	.997
30	1.195	1.117	1.065	1.033	1.013	1.000	.996	.994
35	1.250	1.150	1.083	1.042	1.017	1.000	.994	.991
40	1.325	1.195	1.108	1.054	1.022	1.000	.991	.986
45	1.425	1.255	1.142	1.071	1.028	1.000	.988	.980
50	1.560	1.336	1.187	1.093	1.037	1.000	.982	.972
55	1.750	1.450	1.250	1.125	1.050	1.000	.975	.960
60	2.000	1.600	1.340	1.170	1.068	1.000	.966	.944
65	2.320	1.790	1.440	1.230	1.092	1.000	.955	.925

TABLE 9

URBAN VEHICLE OPERATING COSTS, IN CENTS PER VEHICLE MILE, FOR COMPOSITE VEHICLE, BY AVERAGE VEHICLE SPEED AND LEVEL OF SERVICEABILITY INDEX

Average Speed, mph	Pavement Serviceability Index							
	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
15	6.02	5.80	5.65	5.56	5.51	5.47	5.47	5.47
20	5.68	5.43	5.26	5.16	5.09	5.05	5.04	5.04
25	5.58	5.28	5.08	4.96	4.88	4.83	4.82	4.82
30	5.70	5.33	5.08	4.93	4.83	4.77	4.75	4.74
35	5.96	5.49	5.17	4.97	4.85	4.77	4.74	4.73
40	6.40	5.77	5.35	5.09	4.94	4.83	4.79	4.76
45	7.04	6.20	5.64	5.29	5.08	4.94	4.88	4.84
50	7.96	6.81	6.05	5.57	5.29	5.10	5.01	4.96
55	9.33	7.73	6.66	6.00	5.60	5.33	5.20	5.12
60	11.20	8.96	7.50	6.55	5.98	5.60	5.41	5.29
65	13.85	10.69	8.60	7.34	6.52	5.97	5.70	5.52

TABLE 10

RURAL VEHICLE OPERATING COSTS, IN CENTS PER VEHICLE MILE, FOR COMPOSITE VEHICLE, BY AVERAGE VEHICLE SPEED AND LEVEL OF SERVICEABILITY INDEX

Average	Pavement Serviceability Index							
Speed, mph	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
15	6.92	6.67	6.50	6.40	6.33	6.29	6.29	6.29
20	6.54	6.25	6.05	5.93	5.86	5.81	5.80	5.80
25	6.47	6.12	5.89	5.75	5.66	5.60	5.59	5.58
30	6.60	6.17	5.88	5.70	5.59	5.52	5.50	5.49
35	6.93	6.37	6.00	5.77	5.63	5.54	5.51	5.49
40	7.49	6.75	6.26	5.96	5.77	5.65	5.60	5.57
45	8.31	7.32	6.66	6.24	5.99	5.83	5.76	5.71
50	9.45	8.10	7.19	6.62	6.28	6.06	5.95	5.89
55	11.15	9.24	7.96	7.17	6.69	6.37	6.21	6.12
60	13.62	10.90	9.13	7.97	7.27	6.81	6.58	6.43
65	17.26	13.32	10.71	9.15	8.12	7.44	7.11	6.88

TABLE 11

VEHICLE OPERATING COSTS, IN CENTS PER VEHICLE MILE, BY TYPE OF AREA, TYPE OF ROAD, AND PAVEMENT SERVICEABILITY INDEX

Pavement Serviceability Index	Type of Area and Type of Road					
	URBAN			RURAL		
	2-lane	4-lane undivided	4 or more lane divided	2-lane	4-lane undivided	4 or more lane divided
1.5	5.90	5.60	5.66	7.95	8.05	8.14
2.0	5.43	5.30	5.45	7.84	8.00	8.10
2.5	5.03	5.10	5.26	7.73	7.96	8.05
3.0	4.91	4.94	5.12	7.37	7.70	7.97
3.5	4.86	4.85	5.02	7.06	7.34	7.65
4.0	4.83	4.77	4.94	6.75	7.03	7.30
4.5	4.82	4.74	4.88	6.58	6.84	7.11
5.0	4.82	4.73	4.84	6.43	6.67	6.88

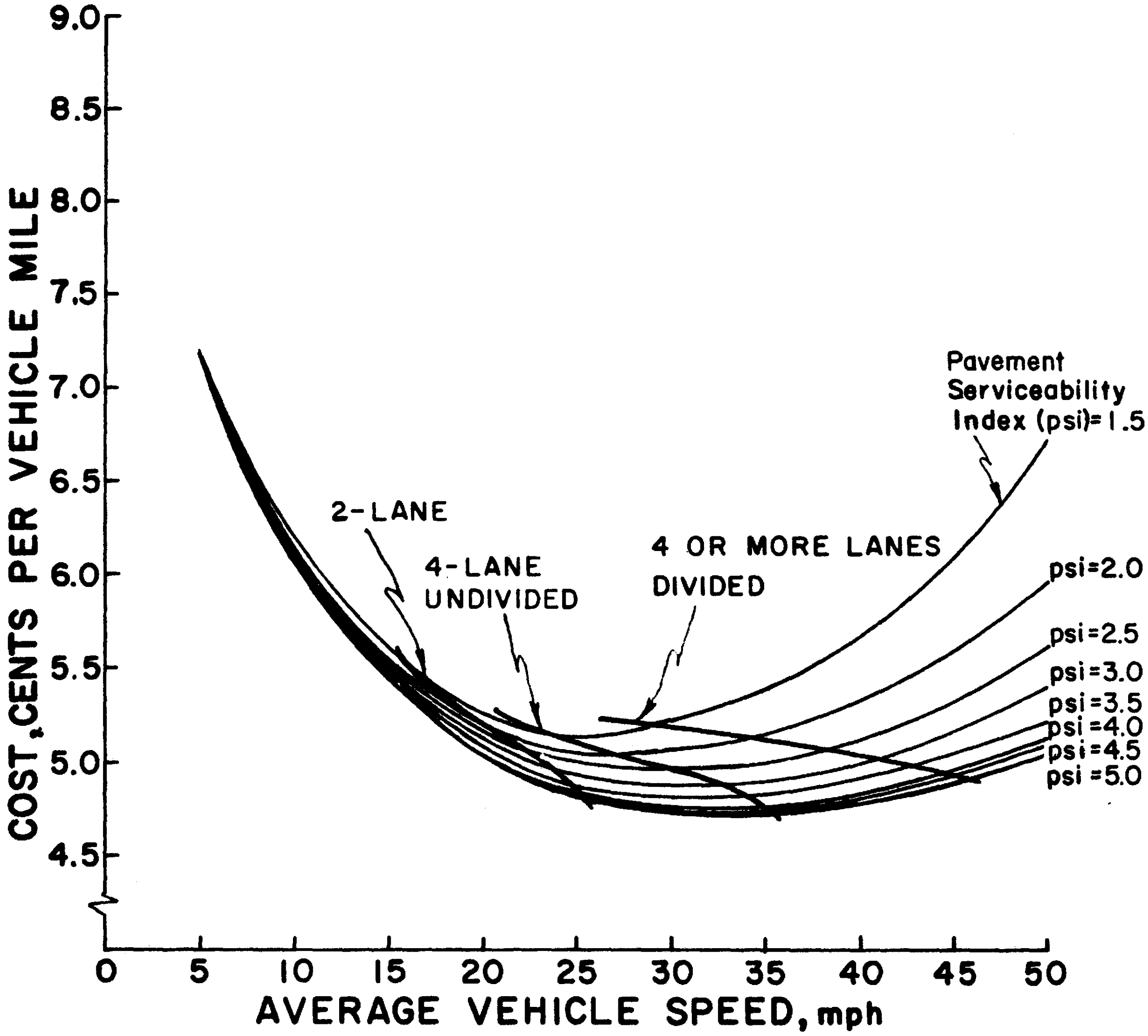

Figure 6: Urban vehicle operating costs, in cents per vehicle mile, related to the pavement serviceability index, the average vehicle speed, and the type of road.

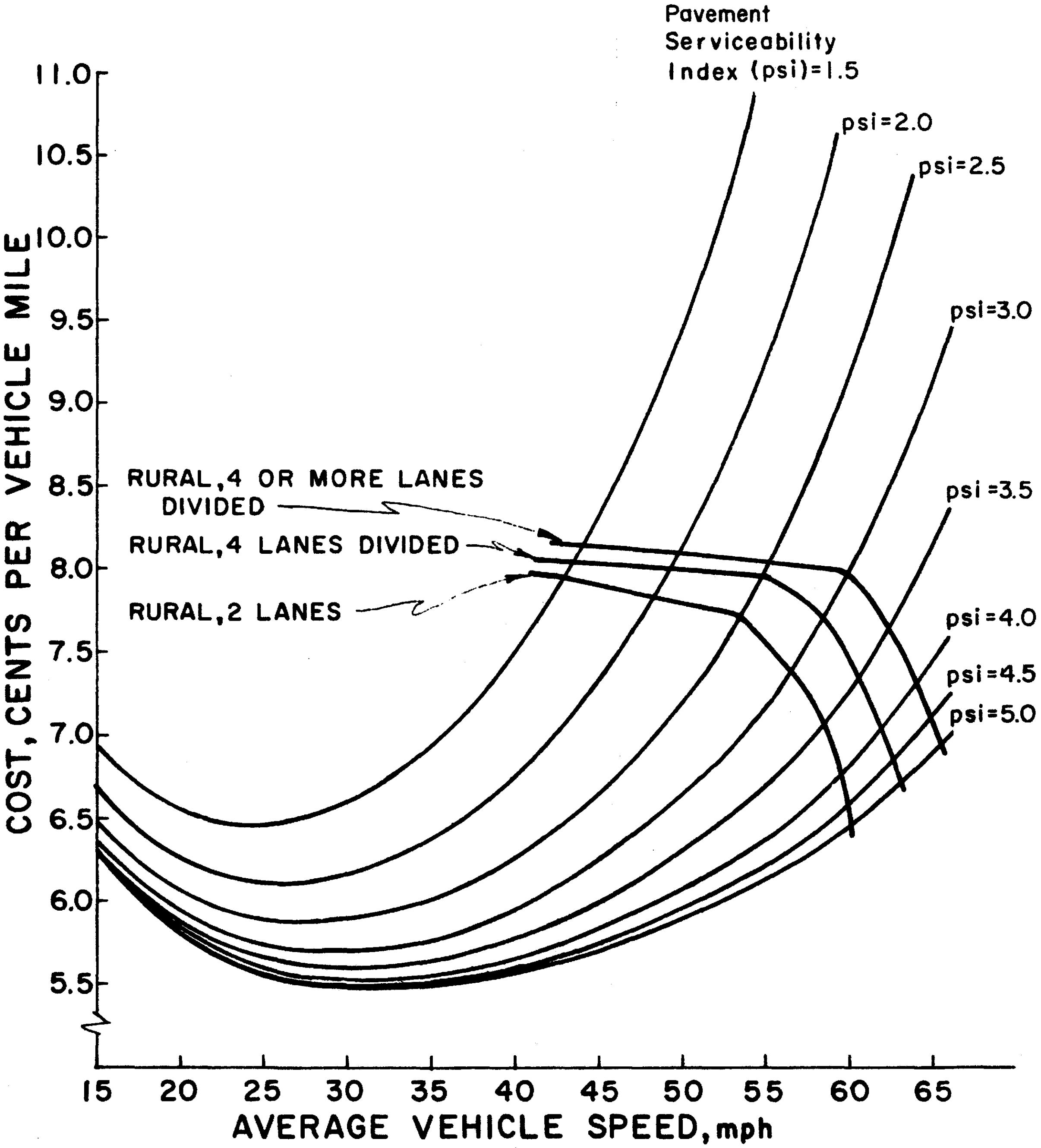

Figure 7: Rural vehicle operating costs, in cents per vehicle mile, related to the pavement serviceability index, the average vehicle speed, and the type of road.

2.5 ACCIDENT COSTS

Because of the nature of existing data on accidents and because of the variability of accidents and accident costs, it is difficult to relate accident costs to the pavement serviceability index. The principal pavement characteristics that affect accidents probably are pavement smoothness (as measured, for example, by the pavement serviceability index) and skid resistance (as measured, for example, by the pavements coefficient of friction at 50 mph).

A pavement's serviceability index generally is considered to be a function of the number of 18-kip equivalent loads that pass over the roadway and of the effect of swelling clay on the pavement. The coefficient of friction, on the other hand, is related to the number of vehicles passing over the roadway, the type of aggregate used in the surface layer, the type of surface layer, and weather conditions.

Ideally, accident rates and costs should be related to both the pavement serviceability index and the coefficient of friction, in addition to non-pavement-related variables. The procedure used in this study is to simply relate accident cost to the pavement serviceability index and type of road. It is assumed, in effect, that the pavement serviceability index and coefficient of friction decrease over time in a manner such that they both can be taken into account by simply relating accident rates to the pavement serviceability index. This assumption is based on the fact that both the pavement serviceability index and the coefficient of friction are related to the amount of traffic that passes over the roadway. It is realized, however, that this is an oversimplification and that future research is needed in this area to derive more complete relationships.

Two types of studies were found that could be used in relating accidents to the pavement serviceability index. Both types of studies were evaluated in a recent report, by Jorgenson and Westat [27], on methods of predicting the change in accident rates associated with different types of safety improvements. The first type of study involved a comparison of accident rates before and after pavements were resurfaced. Jorgenson and Westat reviewed before-after studies from Connecticut, Idaho, Ohio, Oklahoma, and Pennsylvania. There was considerable variability in the data studied, with many of the studies showing increases in accidents as a result of resurfacing operations. Overall, Jorgenson and Westat decided that the Ohio data were the most consistent and recommended their use for predicting accident reductions for pavement resurfacing. These data showed reductions in accidents for pavement resurfacing as follows: (1) a 42% reduction on urban roads with more than 2 lanes; (2) a 44% reduction on rural roads with more than 2 lanes, and (3) a 12% reduction on rural roads with 2 lanes. It was emphasized, however, that these reductions were on roads having a high proportion of accidents involving skidding, and that "resurfacing projects on geometrically low standard roads which are not experiencing a skidding type accident problem tend to show an increase in accidents. The resurfacing probably creates a deceptive appearance causing some drivers to overdrive the highway" [27, p. 46]. Since these percentage reductions in accidents are from before-after type studies, it might be expected that, in the year before the resurfacing, the skid resistance, and probably also the pavement serviceability index, was relatively low, whereas in the year after the resurfacing both were relatively high.

The other type of study reviewed by Jorgenson and Westat was one that related accident rates to the pavement skid resistance, as measured by the coefficient of friction at 50 mph on rural Texas highways [27]. This relationship between the accident rate and the coefficient of friction is given in the first and third columns of Table 12. In the second column of this table are given the pavement serviceability indices that are assumed to be related to the different levels of the coefficient of friction. It might be noted that the percentage reduction in accidents achieved by increasing the coefficient of friction from 0.3 to 0.7 is about 38% which is only 6% less than the percentage reduction in accidents shown by the Ohio data for rural roads with more than 2 lanes.

Based on this information, it seems reasonable to use the ratios of accidents at different levels of the coefficient of friction and the corresponding assumed levels of the serviceability index as multipliers, to be multiplied times the actual rural accident rates in Texas to derive accident rates at different levels of the serviceability index. Column 4 of Table 12 gives these multipliers for rural roads with more than 2 lanes. For rural roads with 2 lanes, it is assumed that the percentage change in the multiplier is about one-fourth of that for roads with more than 2 lanes; the multipliers for rural, 2-lane roads are given in Column 5 of Table 12. These multipliers for 2-lane roads are derived on the basis of the Ohio data that indicated that the percentage change in accident rates due to resurfacing for 2-lane roads was about one-fourth of that for roads with more than 2-lanes.

TABLE 12

RURAL ACCIDENT RATES, RATIOS OF ACCIDENT RATES, AND PAVEMENT SERVICEABILITY INDEX RELATED TO COEFFICIENT OF FRICTION

(1) Coefficient of Friction at 50 mph	(2) Assumed Pavement Serviceability Index	(3) Accidents Per 100 Million Vehicle Miles	(4) Multiplier for 4-lane highways[1]	(5) Multiplier for 2-lane highways[2]
0.1	1.5	380	2.62	1.41
0.2	2.0	280	1.93	1.23
0.3	2.5	210	1.45	1.11
0.4	3.0	170	1.17	1.04
0.5	3.5	145	1.00	1.00
0.6	4.0	135	0.93	0.98
0.7	4.5, 5.0	130	0.90	0.97

[1]Accident rates from Column (3) divided by 145, the accident rate for a serviceability index of 3.5.

[2]Multiplier = 1.0 + 0.25 (Column (4) - 1.0).

Each of the two series of multipliers given in Columns 4 and 5 of Table 12 is relative to a coefficient of friction of 0.5 and a pavement serviceability index of 3.5. The reason for this is that it is further assumed that the average accident rates on rural Texas highways corresponds to this level of the pavement serviceability index.

A recent study [6] of accident rates in Texas determined that the approximate numbers of accidents per hundred million vehicle miles for rural roads were as follows: 2-lane highways:196; 4-lane, undivided highways: 345; and 4-or-more lane, divided highways:100. This same study also determined that the average accident cost was $3,100 in rural areas and $700 in urban areas.

Multiplying these accident rates for Texas by the multipliers from Columns 4 and 5 of Table 12 gives the accident rates at different levels of the serviceability index shown in Table 13. Using these accident rates together with the cost of $3,100 per rural accident gives the accident costs by type of rural road and level of the serviceability index that are shown in Table 14.

No attempt is made to derive accident costs for urban roads. Until further information is developed it is assumed that the accident rates on urban roads are the same at all levels of the serviceability index.

TABLE 13

RURAL ACCIDENT RATES, IN ACCIDENTS PER HUNDRED MILLION VEHICLE MILES, BY TYPE OF ROAD AND LEVEL OF SERVICEABILITY INDEX

Pavement Serviceability Index	2-lane highway	4-lane undivided highway	4 or more lane divided highway
1.5	276	904	143
2.0	241	666	123
2.5	218	500	111
3.0	204	404	104
3.5	196	345	100
4.0	192	321	98
4.5, 5.0	190	311	97

TABLE 14

RURAL ACCIDENT COSTS, IN CENTS PER VEHICLE MILE, BY TYPE OF ROAD AND LEVEL OF PAVEMENT SERVICEABILITY INDEX

Pavement Serviceability Index	2-lane highway	4-lane undivided highway	4 or more lane, divided highway
1.5	0.86	2.80	0.44
2.0	0.75	2.06	0.38
2.5	0.68	1.55	0.34
3.0	0.63	1.25	0.32
3.5	0.61	1.07	0.31
4.0	0.60	1.00	0.30
4.5, 5.0	0.59	0.96	0.30

2.6 DISCOMFORT COSTS

Estimation of the dollar cost of discomfort associated with different roadway conditions is one of the more difficult conceptual problems encountered in the overall problem of estimating user costs.

Some attempts have been made to measure driver tension responses to traffic events by measuring electrical response and perspiration. Even if these responses or other motorist characteristics (e.g., fatigue) can be accurately measured, however, there remains the difficulty of providing dollar values for each level or number of the measured units.

For evaluating the reduction of discomfort, a more promising approach than measuring tension probably is measuring the number of road characteristics and traffic events which cause discomfort and then to determine how much motorists are willing to pay to avoid such road characteristics and events. Some researchers have attempted to measure the number of events and obstacles that impede traffic flow; such obstacles include "...poor road conditions, intersections, vehicles on the left or right or approaching from the roadside, vehicles to be met, etc."[32, p.14]. These obstacles cause driving maneuvers such as speed changes (including stops, starts, accelerations, and decelerations), turns and passing maneuvers. Only one attempt has been made to evaluate how much motorists are willing to pay to avoid speed changes, and the results of that study were inconclusive and difficult to evaluate [31].

Many of the maneuvers that cause speed changes not only cause discomfort but also cause increased travel times. As was discussed previously in section 2.2, motorists adjust their speed to avoid events that cause discomfort. Considered in terms of what they think is their optimum speed under given conditions (i.e., presumably the speed at which they travel under given conditions), what motorists do when they reduce their speed is to increase their time cost but reduce their discomfort cost and possibly their accident and vehicle operating costs. On paved surfaces, motorists change their speed in relation to overall pavement smoothness and also make intermittent speed changes in relation to short stretches of road that are especially bad, or perhaps appear to be especially bad (e.g., patches, holes).

Perhaps the most promising method of evaluating the discomfort associated with different pavement characteristics would be one that determined all costs other than discomfort costs associated with traveling at different speeds on roads with given characteristics, and then inferring, from the actual speeds at which people travel, the implied cost of discomfort. There is, however, a problem associated with this method. Motorists may not know their costs other than discomfort at different speeds (and even if this is admitted, there still remains the problem of determining what motorists think their other costs are). Also, there is the additional problem of determining whether (and, if so, how) the vehicle driver considers other people's costs in arriving at his choice of speed.

In a recent study, Lisco [20] determined that commuters were willing to pay \$1.50 to \$2.50 per day (2-way trip of about 30 miles) for "the privilege of enjoying the comfort of their own cars over that of using transit-this being when the actual overall commuting times [and other costs] are the same." This amounts to about 5 to 8 cents per mile that people were willing to pay for "comfort" to use their private automobiles, as opposed to using public transit. Exactly what is included in this "comfort" evaluation was not determined although it undoubtedly was different for different people and may have included, for example, (1) less uncertainty regarding travel time, (2) the ability to perform some act, such as smoking or listening to the radio, in the automobile, (3) more privacy, (4) less chance of being the victim of a crime, (5) the "pleasure" of driving a car, (6) the car seat being more comfortable than the bus seat, (7) fewer stops, and other speed changes, (8) inconvenience with paying a bus fare, (9) the ability to go shopping or to engage in some other activity on the way to or from work, (10) "prestige" associated with driving an automobile to work, and so forth. Whatever may be included in Lisco's "comfort" term, it is clear that it may be more than simply the "comfort" of riding in a private automobile as opposed to riding in public transit. Nevertheless, Lisco's study does demonstrate that research can provide dollar values for seemingly intangible items. Also, it adds to our general knowledge regarding how much people are willing to pay for "comfort."

The Red Book [2 , pp. 76-77, 126-127], using what may be considered 1959 costs, assigns a cost for discomfort (i.e., lack of comfort and convenience) of 0.75 cents per vehicle mile for operation on loose surfaced roads and of 1.0 cents per vehicle mile for operation on unsurfaced roads. (For paved roads, discomfort costs are assigned on the basis of traffic congestion on the roadway.) In the Red Book, the discomfort costs for inferior pavements are assumed to be independent of vehicle speeds. At the time these discomfort costs were assigned, they were considered to be "conservative" [2 , p. 77]. Taking this into consideration and also considering the general inflation that has occurred since those estimates were made, it seems reasonable to expect current discomfort costs to be higher than those given in the Red Book. In the present study it is assumed that discomfort costs, associated with pavement roughness, for pavement roughness in excess of that for a serviceability index of 4.5, per vehicle mile, for vehicles traveling at 65 miles per hour are as follows:

Pavement Serviceability Index	Discomfort Cost (¢/veh.mi.) at 65 mph
1.5	6.00
2.0	4.00
2.5	2.50
3.0	1.50
3.5	0.75
4.0	0.25
4.5	0.00
5.0	0.00

It is assumed that discomfort increases at an increasing rate with higher speeds and with lower levels of serviceability. The costs for all different speeds are assumed to be those shown in Figure 8. It might be noted that on 4-lane, divided, rural roads the discomfort cost at a serviceability index of 1.5 at 65 miles per hour is 6.0 cents per vehicle mile but is only 2.3 cents per vehicle mile at the actual speed of operation assumed for a serviceability index of 1.5. Thus, even though a maximum discomfort cost of 6 cents per mile is assumed to be possible, the maximum average discomfort cost that is assumed to be experienced is 2.3 cents per vehicle mile. This is because motorists slow down

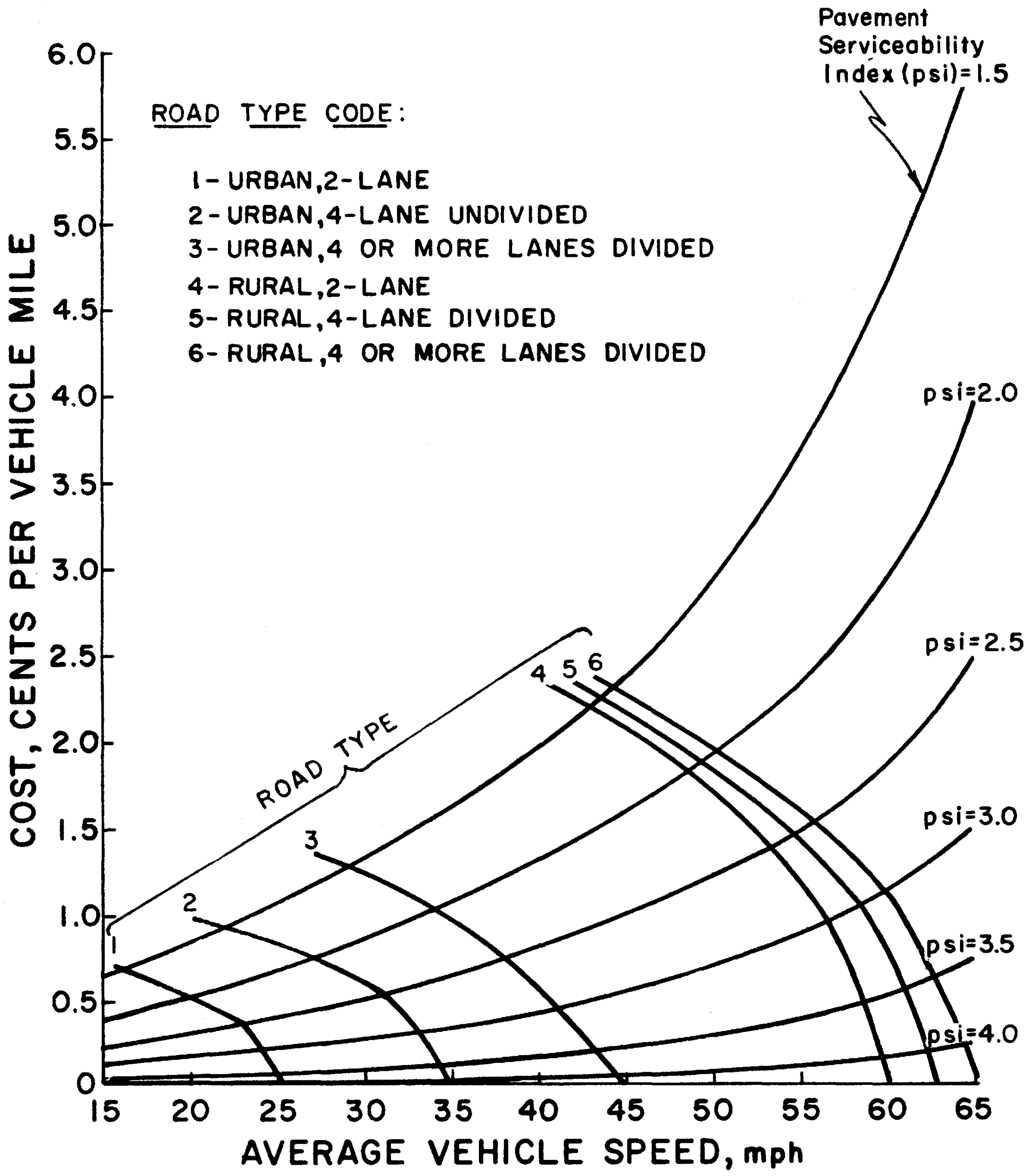

Figure 8: Discomfort costs, in cents per vehicle mile, related to the pavement serviceability index, the average vehicle speed, and the type of road.

to avoid the higher discomfort cost associated with speeds at which they would travel on roads with a higher serviceability index.

The assumed discomfort costs from Figure 8 together with the operating speeds previously given in Table 1 are used to derive the discomfort costs for different roadways at different levels of the pavement serviceability index, and these costs are presented in Table 15.

Table 15

Discomfort Cost, in Cents Per Vehicle Mile, Related to the Serviceability Index and Type of Road

Pavement Serviceability Index	Discomfort Cost in Cents Per Vehicle Mile, by Type of Road					
	Urban			Rural		
	2-lane	4-lane Undivided	4 or more lanes divided	2-lane	4-lane undivided	4 or more lanes divided
1.5	0.70	0.93	1.25	2.20	2.25	2.30
2.0	0.53	0.75	1.05	1.80	1.90	1.95
2.5	0.40	0.55	0.75	1.40	1.50	1.54
3.0	0.20	0.35	0.45	0.95	1.05	1.15
3.5	0.08	0.13	0.20	0.50	0.55	0.65
4.0	0.00	0.02	0.05	0.20	0.20	0.25
4.5	0.00	0.00	0.00	0.00	0.00	0.00
5.0	0.00	0.00	0.00	0.00	0.00	0.00

2.7 TOTAL USER COSTS

The preceding sections of this chapter have presented methods of estimating motorists' costs associated with different levels of the pavement serviceability index on six types of roads. These costs were those associated with travel time, vehicle operation, accidents, and discomfort. Accident costs were estimated only for rural roads, but the other three types of costs were estimated for both rural and urban roads.

Table 16 presents the sum of travel time costs, vehicle operating costs, and discomfort costs for urban roads. In Table 16, these costs are related to the pavement serviceability index and the average vehicle speed. This average vehicle speed is considered to be the average spot speed, with it being assumed that the speed is measured at a mid-block location. These costs for urban areas do not include the extra cost associated with changing speeds and stopping at traffic lights and stop signs and also do not include accident costs.

Tables 17, 18, and 19 present the sums of the costs for travel time, vehicle operation, accidents, and discomfort for rural roads. These costs are related to the pavement serviceability index and the average vehicle speed.

Tables 20 through 25 present the total user costs for different levels of the pavement serviceability index, for the average speeds, from Table 1, at which vehicles are assumed to operate on the six types of roads considered in this study. Thus, these six tables present the actual total user costs that motorists supposedly will experience. Whereas Tables 16 through 19 give total user costs for several different speeds, Tables 20 through 25 give total user costs for a specific speed at each level of the serviceability index.

TABLE 16

TOTAL USER COSTS, IN CENTS PER VEHICLE MILE, RELATED TO AVERAGE VEHICLE SPEED AND LEVEL OF PAVEMENT SERVICEABILITY INDEX, FOR URBAN AREAS

Average Speed, mph	Pavement Serviceability Index 1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
15	33.06	32.58	32.28	32.09	31.95	31.87	31.87	31.87
20	26.32	25.76	25.38	25.13	24.95	24.85	24.84	24.84
25	22.48	21.81	21.34	21.03	20.80	20.68	20.66	20.66
30	20.21	19.40	18.81	18.43	18.14	17.99	17.95	17.94
35	18.89	17.89	17.14	16.64	16.30	16.11	16.05	16.04
40	18.26	17.01	16.06	15.44	15.02	14.78	14.69	14.66
45	18.21	16.60	15.44	14.66	14.11	13.81	13.68	13.64
50	18.78	16.66	15.19	14.19	13.51	13.12	12.93	12.88
55	20.17	17.27	15.36	14.10	13.19	12.67	12.40	12.32
60	22.42	18.50	15.96	14.30	13.09	12.20	12.01	11.89
65	25.94	20.78	17.19	14.93	13.36	12.31	11.79	11.61

TABLE 17

TOTAL USER COSTS, IN CENTS PER VEHICLE MILE, RELATED TO AVERAGE VEHICLE SPEED AND LEVEL OF PAVEMENT SERVICEABILITY INDEX, FOR RURAL ROADS WITH 2 LANES

Average Speed, mph	Pavement Serviceability Index							
	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
15	36.69	36.07	35.68	35.43	35.25	35.16	35.15	35.15
20	29.44	28.73	28.25	27.93	27.73	27.61	27.59	27.59
25	25.35	24.52	23.95	23.57	23.31	23.17	23.14	23.13
30	22.90	21.92	21.22	20.76	20.44	20.27	20.22	20.21
35	21.52	20.32	19.45	18.87	18.49	18.28	18.21	18.19
40	20.91	19.44	18.35	17.64	17.16	16.90	16.79	16.76
45	20.96	19.09	17.76	16.86	16.25	15.92	15.77	15.72
50	21.69	19.26	17.57	16.43	15.67	15.24	15.02	14.96
55	23.36	20.04	17.85	16.41	15.40	14.82	14.51	14.42
60	26.17	21.66	18.74	16.82	15.46	14.67	14.24	14.09
65	30.64	24.59	20.41	17.80	16.00	14.81	14.22	13.99

TABLE 18

TOTAL USER COSTS, IN CENTS PER VEHICLE MILE, RELATED TO AVERAGE VEHICLE SPEED AND LEVEL OF PAVEMENT SERVICEABILITY INDEX, FOR RURAL, UNDIVIDED ROADS WITH 4 LANES

Average Speed, mph	Pavement Serviceability Index							
	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
15	38.63	37.38	36.55	36.05	35.71	35.56	35.52	35.52
20	31.38	30.04	29.12	28.55	28.19	28.01	27.96	27.96
25	27.29	25.83	24.82	24.19	23.77	23.57	23.51	23.50
30	24.84	23.23	22.09	21.38	20.90	20.67	20.59	20.58
35	23.46	21.63	20.32	19.49	18.95	18.68	18.58	18.56
40	22.85	20.75	19.22	18.26	17.62	17.30	17.16	17.13
45	22.90	20.40	18.63	17.48	16.71	16.32	16.14	16.09
50	23.63	20.57	18.44	17.05	16.13	15.64	15.39	15.33
55	25.30	21.35	18.72	17.03	15.86	15.22	14.88	14.79
60	28.11	22.97	19.61	17.44	15.92	15.07	14.61	14.46
65	32.56	25.90	21.28	18.42	16.46	15.21	14.59	14.36

TABLE 19

TOTAL USER COSTS, IN CENTS PER VEHICLE MILE,
RELATED TO AVERAGE VEHICLE SPEED AND LEVEL OF PAVEMENT SERVICEABILITY INDEX, FOR RURAL, DIVIDED ROADS WITH 4 OR MORE LANES

Average	Pavement Serviceability Index							
Speed, mph	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
15	36.27	35.70	35.34	35.12	34.95	34.86	34.86	34.86
20	29.02	28.36	27.91	27.62	27.43	27.31	27.30	27.30
25	24.93	24.15	23.61	23.26	23.01	22.87	22.85	22.84
30	22.48	21.55	20.88	20.45	20.14	19.97	19,93	19.92
35	21.10	19.95	19.11	18.56	18.19	17.98	17.92	17.90
40	20.49	19.07	18.01	17.33	16.86	16.60	16.50	16.47
45	20.54	18.72	17.42	16.55	15.95	15.62	15.48	15.43
50	21.27	18.89	17.23	16.12	15.37	14.94	14.73	14.67
55	22.94	19.67	17.51	16.10	15.10	14.52	14.22	14.13
60	25.75	21.29	18.40	16.51	15.16	14.37	13.95	13.80
65	30.22	24.22	20.07	17.49	15.70	14.51	13.93	13.70

TABLE 20

USER COSTS, IN CENTS PER VEHICLE MILE, RELATED TO THE PAVEMENT SERVICEABILITY INDEX, FOR URBAN ROADS WITH 2 LANES

Pavement Serviceability Index	Type of Cost			
	Time	Operating	Discomfort	Total
1.5	24.74	5.90	0.70	31.34
2.0	19.80	5.43	0.53	25.76
2.5	17.22	5.03	0.40	22.65
3.0	16.50	4.91	0.20	21.61
3.5	15.84	4.86	0.08	20.78
4.0	15.84	4.83	0.00	20.67
4.5	15.84	4.82	0.00	20.66
5.0	15.84	4.82	0.00	20.66

TABLE 21

USER COSTS, IN CENTS PER VEHICLE MILE, RELATED TO THE PAVEMENT SERVICEABILITY INDEX, FOR UNDIVIDED URBAN ROADS WITH 4 LANES

Pavement Serviceability Index	Type of Cost			
	Time	Operating	Discomfort	Total
1.5	18.00	5.60	0.93	24.53
2.0	14.67	5.30	0.75	20.72
2.5	12.77	5.10	0.55	18.42
3.0	12.00	4.94	0.35	17.29
3.5	11.65	4.85	0.13	16.63
4.0	11.48	4.77	0.02	16.27
4.5	11.31	4.74	0.00	16.05
5.0	11.31	4.73	0.00	16.04

TABLE 22

USER COSTS, IN CENTS PER VEHICLE MILE, RELATED TO THE PAVEMENT SERVICEABILITY INDEX, FOR DIVIDED URBAN ROADS WITH 4 OR MORE LANES

Pavement Serviceability Index	Type of Cost			
	Time	Operating	Discomfort	Total
1.5	13.66	5.66	1.25	20.57
2.0	11.65	5.45	1.05	18.15
2.5	10.42	5.26	0.75	16.43
3.0	9.66	5.12	0.45	15.23
3.5	9.21	5.02	0.20	14.43
4.0	9.00	4.94	0.05	13.99
4.5	8.80	4.88	0.00	13.68
5.0	8.80	4.84	0.00	13.64

TABLE 23

USER COSTS, IN CENTS PER VEHICLE MILE, RELATED TO THE PAVEMENT SERVICEABILITY INDEX, FOR RURAL ROADS WITH 2 LANES

Pavement Serviceability Index	Type of Cost				
	Time	Operating	Accident	Discomfort	Total
1.5	9.86	7.95	0.86	2.20	20.87
2.0	8.74	7.84	0.75	1.80	19.13
2.5	7.93	7.73	0.68	1.40	17.74
3.0	7.50	7.37	0.63	0.95	16.45
3.5	7.25	7.06	0.61	0.50	15.42
4.0	7.13	6.75	0.60	0.20	14.68
4.5	7.07	6.58	0.59	0.00	14.24
5.0	7.07	6.43	0.59	0.00	14.09

TABLE 24

USER COSTS, IN CENTS PER VEHICLE MILE, RELATED TO THE PAVEMENT SERVICEABILITY INDEX, FOR UNDIVIDED RURAL ROADS WITH 4 LANES

Pavement Serviceability Index	Type of Cost				
	Time	Operating	Accident	Discomfort	Total
1.5	9.75	8.05	2.80	2.25	22.85
2.0	8.57	8.00	2.06	1.90	20.53
2.5	7.71	7.96	1.55	1.50	18.72
3.0	7.25	7.70	1.25	1.05	17.25
3.5	7.01	7.34	1.07	0.55	15.97
4.0	6.84	7.03	1.00	0.20	15.07
4.5	6.73	6.84	0.96	0.00	14.53
5.0	6.73	6.67	0.96	0.00	14.36

TABLE 25

USER COSTS, IN CENTS PER VEHICLE MILE, RELATED TO THE PAVEMENT SERVICEABILITY INDEX, FOR DIVIDED RURAL ROADS WITH 4 OR MORE LANES

Pavement Serviceability Index	Type of Cost				
	Time	Operating	Accident	Discomfort	Total
1.5	9.64	8.14	0.44	2.30	20.52
2.0	8.48	8.10	0.38	1.95	18.91
2.5	7.65	8.05	0.34	1.54	17.58
3.0	7.07	7.97	0.32	1.15	16.51
3.5	6.78	7.65	0.31	0.65	15.39
4.0	6.63	7.30	0.30	0.25	14.48
4.5	6.52	7.11	0.30	0.00	13.93
5.0	6.52	6.88	0.30	0.00	13.70

CHAPTER 3

METHODS OF EVALUATING PAVEMENT DESIGNS

3.1 METHODS OF ANALYSIS

The five principal economic methods that have been used or suggested for use in comparing alternative engineering designs are: (1) the cost-effectiveness method, (2) the cost-of-time method, (3) the benefit-cost method, (4) the rate-of-return method, and (5) the total-transportation-cost method. All of these methods employ costs stated in money terms (not simply in terms of physical inputs). The cost-effectiveness method entails the use of effectiveness measures stated in terms of physical (non-monetary) units. The cost-of-time method uses all benefits, stated in dollar terms, except the value of motorists' time. The other three methods (benefit-cost, rate-of-return, and total-transportation-cost) use all benefits, or cost savings of motorists, stated in terms of money.

3.1.1 Cost-Effectiveness Method

The cost-effectiveness method is used to compare alternatives and, in order to use it, the costs and levels of effectiveness of each alternative must be determined. Costs usually are represented by the present worth of all initial and future costs, less the present worth of the salvage value that the alternative has at the end of its life. This cost often is annualized for use in comparisons. The level of effectiveness is determined by the values that the measures of effectiveness have for a given alternative. These measures might be, for example, the pavement serviceability index, the pavement's coefficient of friction, the number of vehicle accidents, the average vehicle speed, and so forth. It is customary to state the magnitudes of the measures of effectiveness and to give the times at which they occur; that is, the physical effectiveness measures are not stated in present worth terms and often are calculated for one "average" year. There are two widely used cost-effectiveness criteria: the equal-cost criterion and the equal-effectiveness criterion. The equal-cost criterion is used to compare alternatives with equal cost; the alternative that is considered most effective is the preferable alternative. The equal-effectiveness criterion is used to compare alternatives with equal effectiveness; the alternative that is least costly is considered the preferable alternative.

Extensions for these two criteria are needed because of the following considerations: (1) when use of the equal cost criterion is attempted and there are several measures of effectiveness, one alternative may not be the best for all measures of effectiveness, and (2) there often are various alternatives with several levels of cost and effectiveness, and a criterion is needed for choosing the combined level of cost and effectiveness that is best. To solve the first of these problems, weights can be assigned to the measures of effectiveness, which results in one weighted effectiveness measure. If the proper amounts of dollars are used as weights, and the ratio of effectiveness to cost is determined, then the cost-effectiveness analysis becomes, in effect, a benefit-cost analysis. To solve the second problem, the decision-maker must devise some rule stipulating how much extra cost he is willing to incur to obtain extra effectiveness. In practice, when the cost-effectiveness method has been used, no explicit weights have been assigned to the measures of effectiveness, and no explicit rule stating the value of this extra effectiveness has been formulated.

Much has been written regarding systems analysis and its relationship to cost-effectiveness analysis, especially as it pertains to military systems. A concise discussion of the history of military systems analysis is given by Quade [25], who has explained the distinction between systems analysis and cost-effectiveness analysis in the following way:

> As commonly used in the defense community, the phrase 'systems analysis' refers to formal inquiries intended to advise a decisionmaker on the policy choices involved in such matters as weapons development, force posture design or the determination of strategic objectives.
>
> Each such (systems) study involves as one stage a comparison of alternative courses of action in terms of their effectiveness and cost. When, as often happens, this stage requires major attention, the entire study is sometimes called a cost-effectiveness analysis.

The distinction is not one of principle but of emphasis. Quade [25] emphasizes that to qualify as a systems analysis, a study must consider the entire problem as a whole; thus a systems analysis usually involves

> ...a systematic investigation of the decisionmaker's objectives and of the relevant criteria; a comparison--quantitative where possible - of the costs, effectivenesses, and risks associated with the alternative policies or strategies for achieving each objective; and an attempt to formulate additional alternatives if those examined are found wanting.

Quade [24,26. Also see 15, 16, 18] mentions several "pitfalls" that often are encountered in cost-effectiveness analysis:

1. There often is an overemphasis on problem formulation.
2. Sometimes the model is overemphasized, to the neglect of the question.
3. There sometimes is concentration on statistical uncertainties, rather than "real" uncertainties.
4. Occasionally persons conducting the cost-effectiveness

analysis have a "cherished belief" which leads to "attention bias," and this is the most frequent cause of the failure to consider full range of alternatives. This often takes the form of an unconscious adherence to a "party line" of the organization.

5. The decision-maker sometimes attempts to ease his job by transferring a portion of his decision-making function to a model.

Heymont, Byrk, Linstone, and Surmeier [14] point out that there often are factors that decision-makers must consider that cannot be anticipated by persons conducting cost-effectiveness analyses. Thus, it is important that all factors entering into any cost-effectiveness analysis be carefully documented, so that the decision-maker is fully aware of all factors that were considered. These authors also summarize many important factors that should be considered in systems and cost-effectiveness analyses. Although their discussion is concerned with military operations, most of the information is applicable to any situation in which alternatives are compared.

3.1.2 Cost-of-Time Method

In the cost-of-time method [9], all benefits, except the time savings of motorists, and all costs are stated in annualized or present-worth dollars. The cost-of-time is defined as being equal to the present worth of initial and future costs, less salvage value and less the present worth of all benefits <u>except</u> time, all divided by the present worth (in hours) of time savings of motorists. According to this method, projects with the smaller cost-of-time (including negative values) are most desirable. It is possible, of course, to use a procedure similar to the cost-of-time method for any situation in which all benefits except one can be stated in dollar terms. Moreover, it can be extended to a consideration of some types of benefits stated in dollar terms and several types of benefits not stated in dollar terms, with the extreme case being the simple cost-effectiveness method in which no benefits are stated in dollar terms.

3.1.3 Benefit-Cost Method

The benefit-cost method [10,21,23] of analysis entails the use of a benefit-cost ratio which is the ratio of the present worth of benefits (stated in dollar terms) taken over the life of a project to the present worth of initial capital costs and future costs, less the present worth of the salvage value. The project with the largest benefit-cost ratio is considered to be the best project.

According to Turvey and Prest [49], the benefit-cost method has been used extensively for evaluating water resource projects [10,21] and has also been used in evaluation of projects dealing with transportation, land usage, health, and education. Among the questions which Turvey and Prest [23, p.158] emphasize as being important to benefit-cost formulations are the following:

1. Which costs and which benefits are to be included?
2. How are they to be valued?
3. At what interest rate are they to be discounted?
4. What are the relevant constraints?

Turvey and Prest emphasize that there are many different viewpoints regarding benefit-cost analysis. As an example of the pessimistic viewpoint, they [23, p. 200] quote Arthur Smithies' two conclusions about benefit-cost analyses:

> First, judgment plays such an important role in the estimation of benefit-cost ratios that little significance can be attached to the precise numerical results

> obtained.... Second, competition is likely to drive the agencies (competing for limited funds) towards increasingly optimistic estimates; and far from resolving the organizational difficulties, computation of benefit-cost ratios may in fact make them worse.

In this connection, Turvey and Prest [23, p. 203] conclude the following:

> The case for using cost-benefit analysis is strengthened, not weakened, if its limitations are openly recognized and indeed emphasized. It is no good expecting this technique, at any rate in its present form, to be of any use if a project is so large as to alter the whole complex of relative prices and outputs in a country. It is no good expecting those fields in which benefits are widely diffused, and in economic costs or benefits, to be as cultivable as others. Nor is it realistic to expect that comparisons between projects in entirely different branches of economic activity are likely to be as meaningful or fruitful as those between projects in the same branch. The technique is more useful in the public utility area than in the social-services area of government.

Of course, many of the comments by Turvey and Prest concerning benefit-cost analysis apply to the other methods of analysis as well.

In the highway field, the American Association of State Highway Officials has promoted the use of benefit-cost analysis for project-design-level determination, in their publication commonly known as the "Red Book" [2]. In situations where there are several alternatives, the Red Book recommends that a benefit-cost ratio be used to compare each of these alternatives to the existing condition. It is further stated that in some situations there may be an advantage in calculating what is called a "second benefit ratio." Procedures for calculating the second benefit ratio are given in an appendix. AASHO says that the benefit-cost analysis recommended by them in the Red Book,

> ...is not an economic analysis in the broad sense and cannot be used as such. It is an analysis of the relation of road user benefits to capital (and maintenance) costs. It cannot be used to determine the worth of a proposed investment but it can be of

> great assistance in comparing alternates in location and design for a proposed improvement and, when used with other factors can be of assistance in determining priorities of several proposed improvements [2, p. 10].

The Red Book states that the recommended benefit-cost analysis is not an economic analysis in the broad sense because land and community benefits and the financial aspects of the system are not considered. Land and community benefits, according to the Red Book, include changes in land values, business and tax receipts, and other "social, protective, and welfare gains" that the community may receive. The benefits which are considered in the Red Book are changes in road user costs - specifically savings in time, vehicle operating costs, accidents, and discomfort.

3.1.4 Rate-of-Return Method

The rate-of-return method makes use of a formulation with which is calculated the rate of return on the initial capital investment. It is presumed that there is an initial capital investment, and that there are future costs and benefits for each project. The rate of return which equates the present worth of all future benefits less all future costs, plus the present worth of the salvage value, to the initial capital cost, is the rate of return. Using this method, those projects with the higher rates of return are considered the preferable projects.

3.1.5 Total-Transportation-Cost Method

In the total-transportation-cost method, the total transportation cost is calculated as the sum of the present worths of initial capital costs, future project costs, and future road user costs, less the present worth of the project salvage values. Using this method, projects with the lowest total transportation cost are considered preferable.

3.2 COMPARISON OF METHODS OF ANALYSIS

Each of the methods discussed above can be used to compare alternatives. They also can be used to determine the level of expenditure on a particular project, with use of a "rule" or, in the case of the cost-effectiveness method, with the explicit use of judgment. In many cases, it may be necessary to simultaneously determine both the level of expenditure and the preferred alternative. In fact, different levels of expenditure on a particular project usually can be considered as different alternatives.

If the level of expenditure is unconstrained, except for some rule which determines the cut-off level of expenditure on individual projects, there are conditions outlined below, under which the benefit-cost method, the rate-or-return method, the total-transportation-cost method, and the cost-of-time method all indicate the same optimum level of expenditure on each project. The cut-off level of expenditure on an individual project is defined as the optimum level of expenditure as determined by a specific rule dependent upon the method of analysis being used. For the benefit-cost method, the cut-off level is that benefit-cost ratio which rules that expenditures will be made up to the level at which marginal benefit equals marginal cost (or, for indivisible expenditure increments, to the level at which the ratio of incremental benefits to incremental costs, first becomes less than one).

For the rate-of-return method, the level of expenditure on a project is increased to that level at which the rate of return at the margin of expenditure equals the minimum acceptable rate of return. For rational expenditure determination, this minimum rate of return should equal the interest rate used for discounting in the other methods of analysis.

If the total-transportation-cost method is used, the level of expenditure on a project is increased to that level at which total transportation cost stops decreasing. In effect, this rule stipulates that highway costs should be increased if decreases in user costs more than offset the increase in highway costs. Since these user cost decreases are the benefits which are used in the benefit-cost method, the total-transportation-cost method and the benefit-cost method usually give the same results; however the total-transportation-cost method may yield misleading results in some situations if the highway analyst does not understand fully the implications of the use of the method. For example, decreases in user costs may result because a particular type of design causes decreased travel. In an extreme case, if the goal is to minimize total transportation cost, then the prescribed action would be to have no expenditure and no travel. A misleading interpretation such as this results from the use of decreases in user costs as estimates of benefits.

If the cost-of-time method is used, expenditure is increased if the cost of time for the increment of expenditure is not greater than some maximum acceptable level. For this method to give the same results as the other methods, this maximum acceptable cost of time per hour of time saved should equal the value of time per hour which is assigned to time savings in calculating benefits for use with the other methods.

The above discussion has indicated that if the level of expenditure is unconstrained, except by optimizing rules, then all four of the discussed methods of analysis will indicate the same optimum level of expenditure. If the level of expenditure is constrained (i.e., if there is a budget constraint), then this conclusion is not, in general, valid.

Even with a budget constraint that limits the level of expenditure such that all project increments that meet the acceptance criteria cannot be enacted within the budget period, three of the above named methods - all except the rate-of-return method - prescribe the same level of expenditure on each project.

If the budget constraint limits expenditure, such that not all increments of each project that have benefit-cost ratios greater than one or rates of return greater than the minimum acceptable level can be constructed, then the rate-of-return method and the benefit-cost method will not give the same results if there are any costs other than initial capital costs. The extent of the difference in results between the two methods depends upon the ratio of variable costs to initial costs and upon the length of the analysis period. Use of the benefit-cost method results in the choice of projects and project increments that maximize the benefits obtainable from a given amount of total cost, including initial capital cost and future cost. Use of the rate-of-return method results in choices that maximize the benefits obtainable from a given amount of initial capital cost. Eckstein [16, pp. 62-63] explains the following:

> ...if in each year, those projects are started which have the highest benefit-cost ratios, and if the marginal increment of each project has a benefit-cost ratio equal to the cutoff ratio of the program in the period, then the total return on federal expenditure will be maximized. Federal expenditure is considered the rationed commodity, and given this condition the present value of the future income stream that can be created is maximized.
>
> . . .

> It can thus be seen that the choice of expenditure criterion is determined by the choice of the budgetary constraint which is assumed to limit the program.

Thus, if the budget constraint dictates a cut-off level giving, on the marginal increment of expenditure for each project, benefit-cost ratios greater than one and rates of return greater than the minimum acceptable rate of return, then the choice of criteria depends upon whether total cost or initial capital cost is assumed to be the relevant constraint. If used consistently, the total-transportation-cost method and the cost-of-time method will give the same results as the benefit-cost method and thus will yield different results than will the rate-of-return method.

The cost-effectiveness method of analysis differs from the other methods in that the benefits are stated in various physical units instead of dollars. As was mentioned previously, the cost-effectiveness method is used mainly in terms of the equal-cost criterion or the equal-effectiveness criterion. These criteria are not for the purpose of determining the level of expenditure on projects nor, in general, for determining the best projects except in a partial sense. These two criteria, however, do eliminate some projects and project increments.

3.3 DETERMINATION OF PRIORITIES

The previous discussion has indicated that the cost-effectiveness method of analysis can be used for comparing alternate designs if all projects either cost the same or have the same effectiveness. The decision-maker must use his own judgment or employ some other method of analysis in those situations in which neither the equal-effectiveness criterion nor the equal-cost criterion can be used. Also, it was pointed out that the cost-effectiveness method is not meant to be used for determining priorities. The other methods can, however, be used for this purpose if similar projects are compared, or if it is felt that all benefits and costs can be estimated accurately. Of these other methods, the benefit-cost method is the most widely accepted and the most widely used.

The American Association of State Highway Officials recommends the use of benefit-cost analysis to determine the amount of expenditure on particular highway projects. This group further recommends that benefit-cost analysis not be used for priority determination, that is, for determining which of several roadway improvements has priority. The principal reason the highway officials do not suggest the use of benefit-cost analysis in priority determination is that, with the procedures outlined in the Red Book, such analysis omits consideration of land and community benefits. To the extent that land and community benefits vary for different levels of design, this same criticism also applies to the use of benefit-cost analysis for determining the amount of expenditure on particular highway projects.

Spending of scarce highway funds in a way that maximizes total benefits over time necessitates not only that the benefit-cost criterion be used to determine the level of expenditure on each project; it is also necessary that the marginal benefits per dollar of expenditure be equal for all roadways. The failure to recognize this latter point probably is related to the misconception that total benefits are maximized when the ratio of benefits to costs is maximized. Although it sometimes is stipulated that a second benefit-cost ratio may be used, the Red Book gives no special reason for such a calculation. Moreover, even if a second ratio is calculated, only one increment of expenditure above the level of expenditure that maximizes the ratio of benefits to costs is considered. In effect, not only is a second ratio required in many cases for a correct analysis, but also a third, a fourth, and so on, until all increments which give more benefits than costs are considered. The primary reason the Red Book stipulates that incremental ratios may be used, but are not necessary, is that usage of the ratios may give negative or confusing ratios. Negative and confusing ratios can be avoided, however, by using a procedure that involves an incremental analysis and by omitting from consideration those alternatives that cost the same or more but give the same or less benefits than other alternatives.

Eckstein argues that incremental benefit-cost ratios must be used for the best allocation of funds. Even if it is agreed that incremental ratios are to be used, it still is necessary to determine whether additional increments of expenditure are to be made on particular projects. Eckstein points out that to have an optimal amount of expenditure on each project requires that the last increment of expenditure on each project within the budget have an incremental benefit-cost ratio larger than any feasible increment that is not included within the expenditure budget. The Red Book, on the other hand, takes the position that benefit-cost analyses usually cannot be used in priority determinations.

The above discussion focuses on the methods of analysis which are used, or could be used, to compare alternatives and to make priority determinations. It should be emphasized, however, that the overall decision-making framework includes not only the method of analysis used in comparing alternatives, but also the selection of the alternatives which are considered. Choice of the appropriate method for comparing alternatives thus does not assure that the more efficient alternatives will be considered. It only guarantees that, if the more efficient alternatives are considered, they will be recognized as being more efficient.

3.4 CHOICE OF METHOD

The five principal economic methods of comparing alternative engineering designs have been discussed and compared in the three preceding sections of this chapter. Three of these methods make use of motorists benefits calculated in dollar terms. The other two methods, cost-effectiveness and cost-of-time, do not state all benefits in dollar terms, and thus would not be used with the estimates developed in this report. Of the three methods that use benefits stated in dollar terms, it appears that either the benefit-cost method or the total-transportation-cost method would be preferred for comparing pavement design strategies, since these two methods would use total pavement cost as the relevant constraint. The rate-of-return method also would be acceptable, if the overall budget is not constrained.

Therefore, if motorist benefits can be estimated accurately, it can be argued that either the benefit-cost method or total-transportation-cost method should be used to compare pavement strategies. However, until pavement-related benefits can be estimated more accurately than is possible with current knowledge, it does not appear that any of these methods employing dollar benefits is necessarily preferable to the cost-effectiveness method. The next chapter includes a discussion of the cost-effectiveness method currently used in the Texas Pavement Design System and explains how benefit estimation can be included in this system, either directly or indirectly.

CHAPTER 4

USE OF BENEFITS IN PAVEMENT DESIGN

4.1 CURRENTLY-USED METHOD AND COMPUTER PROGRAMS

The Texas Pavement Design System of the Texas Highway Department includes two computer programs, one for flexible pavements and one for rigid pavements. Each of these compares pavement design strategies on the basis of the cost of providing a given level of effectiveness. Pavement effectiveness is measured by the pavement serviceability index. Costs that are considered include initial and future pavement costs and motorists' costs associated with disruption of traffic during pavement overlay operations.

The method of analysis currently used in the computer programs is, in the terminology of Chapter 3, the cost-effectiveness method, employing the equal-effectiveness criterion. Each of the computer programs considers a large number of pavement design strategies, each of which provides the same level of effectiveness, and ranks these strategies in order of ascending cost. All of the strategies that are compared have equal effectiveness, in that each strategy's minimum pavement serviceability index is expected to always exceed some level specified by the program user. The computer program output lists a number of the design strategies that meet the effectiveness criterion at least cost.

In the current method of analysis, no attempt is made to consider measures of pavement quality other than the pavement serviceability index, and no attempt is made to relate the pavement serviceability index to motorists' benefits. As was discussed in Chapter 3, the cost-effectiveness method does not provide a guide for choosing the level of effectiveness and does not consider motorists' benefits in a comprehensive manner. Ways in which the currently-used cost-effectiveness method might be extended through the use of estimates of motorists' benefits are discussed in the next section of this chapter.

4.2 METHOD OF INCLUDING BENEFITS

There are two principal ways in which motorists' benefits might be used to modify the current cost-effectiveness approach used in the pavement design computer programs. First, the benefit-cost method of analysis could be used in the computer programs. There are, however, two reasons why this approach probably should not be used at this time: (1) little confidence can be placed in the estimates of benefits, and (2) the current computer programs are not used in priority analyses, and thus the benefit-cost method cannot be used properly, as was discussed in Chapter 3. The second principal way in which benefit estimates can be used is through performing sensitivity analyses of motorists benefits under different situations and using the results to supplement the currently-used cost effectiveness analysis. These sensitivity analyses would provide guidelines regarding the computer program input variable designated as the minimum allowable pavement serviceability index. The result of the sensitivity analysis would be a series of such input variables, each of which would be considered desirable under different situations. This approach also could be extended to show how the minimum PSI might differ not only for different roads but for different performance periods within the same design strategy. Also, the decision criteria can be expanded to include increasing cost of maintenance, in addition to increasing user costs, as a reason for overlaying a road. Such an expanded decision criteria probably would better fit actual decision making and would also be a more complete optimization procedure.

CHAPTER 5

LIMITATIONS OF BENEFIT MEASUREMENT AND RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 LIMITATIONS OF MODEL AND DATA

As was mentioned in Chapter 2, the attempt made in this report to relate user costs to the pavement serviceability index is constrained by the lack of basic research in this field. Therefore, the model presented in the report may best be viewed as a way of approaching the problem and a way of determining research needs and not as providing precise estimates of user costs.

The basic limitation of the overall benefit model presented in this report is that it attempts to relate user costs to only one pavement quality measure, the pavement serviceability index. Another limitation of the overall model is that many roadway and traffic variables are not considered, the principal exception being that "type of road" is considered as a variable.

There are several limitations to the data used, the basic limitation being the use of assumed values based on either no concrete information or very limited information. For speed estimates, speed distributions were assumed. Only one study was found that showed the effects on speeds of overlays, and it did not record the pavement serviceability index before and after the overlays. Similarly, the information on operating costs, accident costs, and discomfort costs are basically assumed values even though literature was cited that formed the basis for arriving at the assumed values. Until additional research is performed, it will not be possible to derive more accurate measures of benefits. Thus, the results of this study should be used only in providing research goals and in sensitivity analyses, as is discussed in the next section.

5.2 RECOMMENDATIONS FOR FUTURE RESEARCH

Since the estimates of motorists' pavement-related benefits presented in this report were developed using numerous assumptions, little confidence can be placed in these estimates as precise measures to be used in benefit-cost analyses. Nevertheless, the research does provide indications of where research is needed if the model is to be further developed.

As a short-term goal, it is recommended that the model be checked in sensitivity analyses to determine guidelines regarding the most desirable minimum serviceability index for different types of roads, amounts of average daily traffic, etc. As was discussed in Chapter 4, these sensitivity analyses of motorists benefits would entail the use of benefit-cost analysis (employing imperfect measures of benefits) to supplement the currently-used cost-effectiveness analysis. That is, sensitivity analyses using the benefit model would supplement the current method by providing guidelines regarding the computer program input variable designated as "minimum allowable pavement serviceability index." If this were done, the method would not be simply a "cost-effectiveness method" but rather would be a "cost-effectiveness method, with indirect use of benefit-cost analysis."

A longer-term research goal would be the improvement of the benefit models presented in this report. The overall objective of such improvement would be (1) to provide improved guidelines regarding the best minimum acceptable pavement serviceability indices for different situations, or (2) to change the computer programs being used from the cost-effectiveness method to the benefit-cost method. One way in which the overall benefit model can be improved is by determining how pavement variables other than the pavement serviceability index affect motorists' economic benefits.

For example, the accident cost model could be expanded to include both the pavement serviceability index and some measure of skid resistance as independent variables, instead of assuming that these two measures of effectiveness are directly related as was done in this report. In addition to expanding the benefit models to include other pavement variables, they probably should also be expanded to cover other roadway and traffic variables.

There also are several ways in which the specific benefit models presented in this report can be improved by further research. Each of these specific benefit models (relating time, operating, accident, and discomfort costs to the pavement serviceability index) considered vehicle speeds to be the critical variable in determining costs. Therefore, a considerable improvement could be made in the benefit models if vehicle speeds could be accurately determined for different levels of the pavement serviceability index on different types of roads. Of course, variables other than vehicle speed, pavement serviceability index, and type of road probably should be considered. One possible way of measuring such speeds would be to measure spot speeds on the same or different roadways, where all variables except the pavement serviceability index are approximately the same; this would be a cross-section study done at one point in time. Another possible way of measuring such speeds would be over time, at specific locations on the same roadway; the objective would be to determine how speeds change at a specific roadway location as the pavement serviceability index changes over time. An especially interesting sub-case of this approach would be to measure speeds at a specific location immediately before and after pavement overlays; this sub-case has the advantage of controlling many of the variables that change over time or change with roadway characteristics, but has the disadvantage of considering only low and high levels of the pavement serviceability index.

In addition to research on vehicle speeds, individual studies should be performed to develop better estimates of how pavement characteristics affect vehicle operating costs, accident costs, and discomfort costs. Such research would be directed toward the specific limitations discussed in the first part of this chapter.

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APPENDIX A

AIR AND NOISE POLLUTION

In addition to the four types of user costs considered in Chapter 2, there are other user and non-user effects of pavement smoothness. Two of these effects that have received increasing attention in recent times, especially with regard to travel in urban areas, are air and noise pollution. (However, noise pollution as related to pavement smoothness and affecting motorists can be considered to be included in the discomfort costs considered in Chapter 2.)

There have been no successful attempts to evaluate the cost in dollar terms of air and noise pollution. However, recent studies have documented some of the effects of such pollution and have estimated how pollution is related to vehicle and roadway characteristics.

In general, studies [17] have shown that air pollution per mile of vehicle travel is lower for higher speeds of travel, as is indicated in Table A-1 and Figures A-1 and A-2. Therefore, since vehicles travel faster on pavements with higher serviceability indices, there is less air pollution the higher the level of the pavement serviceability index.

Another study [11] has indicated that vehicle noise is less on smoother pavements but increases with increasing vehicle speeds. This relationship is shown in Figure A-3 for individual passenger vehicles. In Figure A-3, dBA denotes the sound pressure levels in decibels measured with a frequency weighting network corresponding to the A-scale on a standard sound level meter. In Figure A-3, three functions are plotted corresponding to three pavement types. These pavement types and the equation for each are as follows:

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ace:

2. Moderately rough asphalt surface and a rough concrete surface typical of freeway construction:

   dBA at 25 ft. = 23 + 30 Log Speed

3. Very smooth, nearly new asphalt pavement which was compact, with little surface roughness and voids of very small size in the surface:

   dBA at 25 ft. = 18 + 30 Log Speed

In general it can be concluded that smoother pavements reduce noise; even though the amount of reduction in noise is diminished by the fact that vehicles travel faster on smoother pavements, this diminution is relatively less important than the direct smoothness effect.

TABLE A-1

ESTIMATED EXHAUST EMISSIONS FROM AUTOMOBILES OF VARIOUS MODEL YEARS

Model Year	Carbon Monoxide (pounds/mi)	Hydrocarbons (pounds/mi)	Oxides of Nitrogen (pounds/mi)
Pre-1968	$2.46\ s^{-.85}$	$.104\ s^{-.66}$	.0125
1968-69	$.54\ s^{-.48}$	$.045\ s^{-.45}$	.0125
1970-72	$.36\ s^{-.48}$	$.030\ s^{-.45}$	.0125
1973-74	$.36\ s^{-.48}$	$.030\ s^{-.45}$	.0066
1975-79	$.17\ s^{-.48}$	$.0067s^{-.45}$	.0022
1980 and on	$.074s^{-.48}$	$.0034s^{-.45}$	.0011

where s is the average vehicle speed in miles per hour.

Source: Ref. 17.

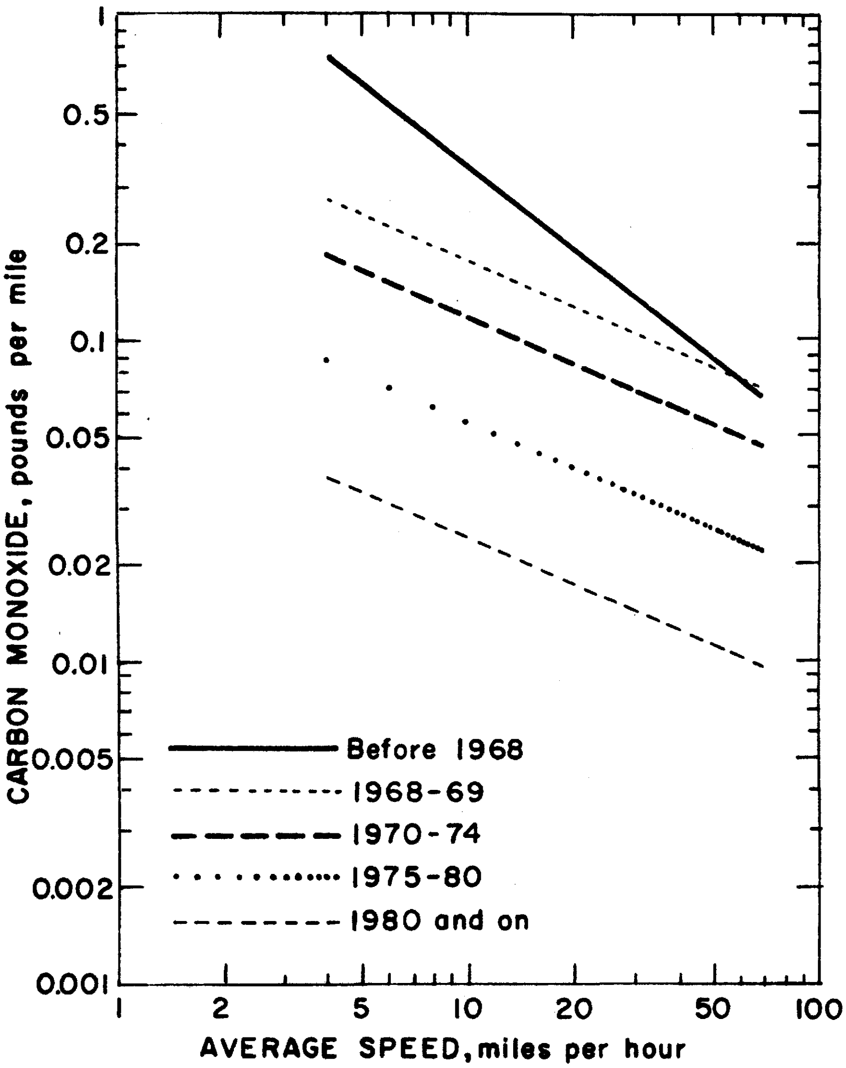

Figure A-1: Exhaust emissions of carbon monoxide from automobiles of various model years (Source: Reference 17).

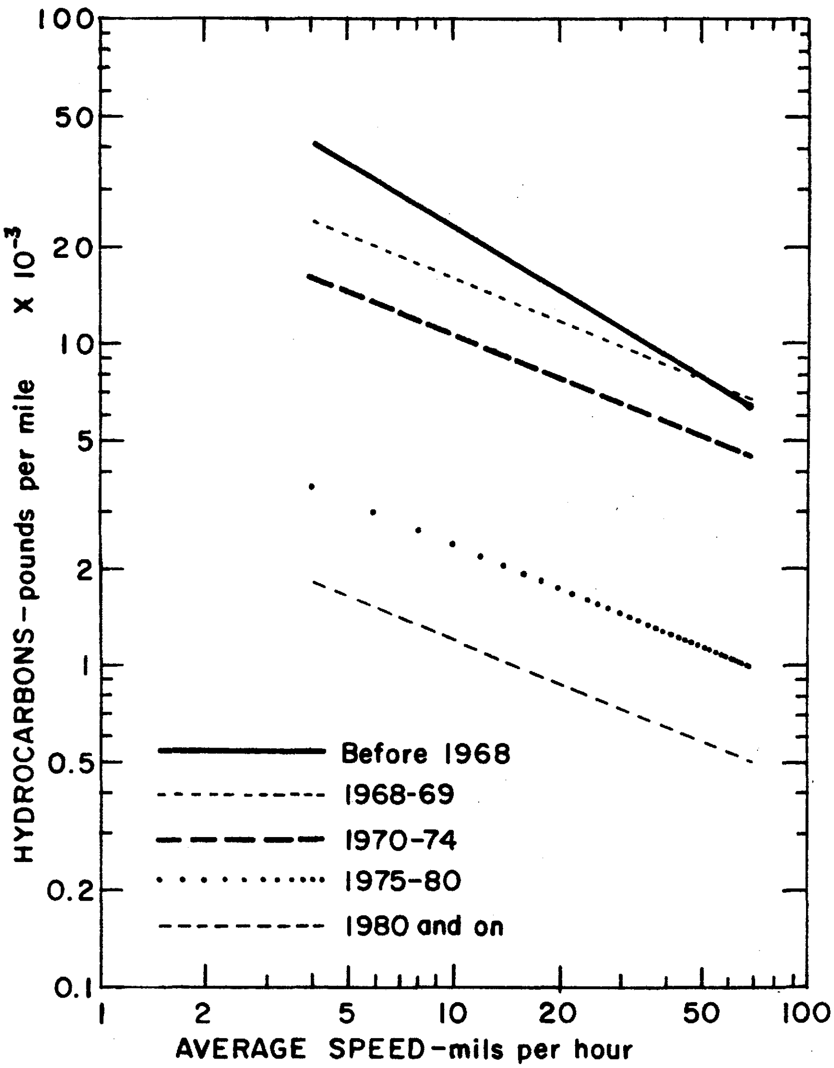

Figure A-2: Exhaust emissions of hydrocarbons from automobiles of various model years (Source: Reference 17).

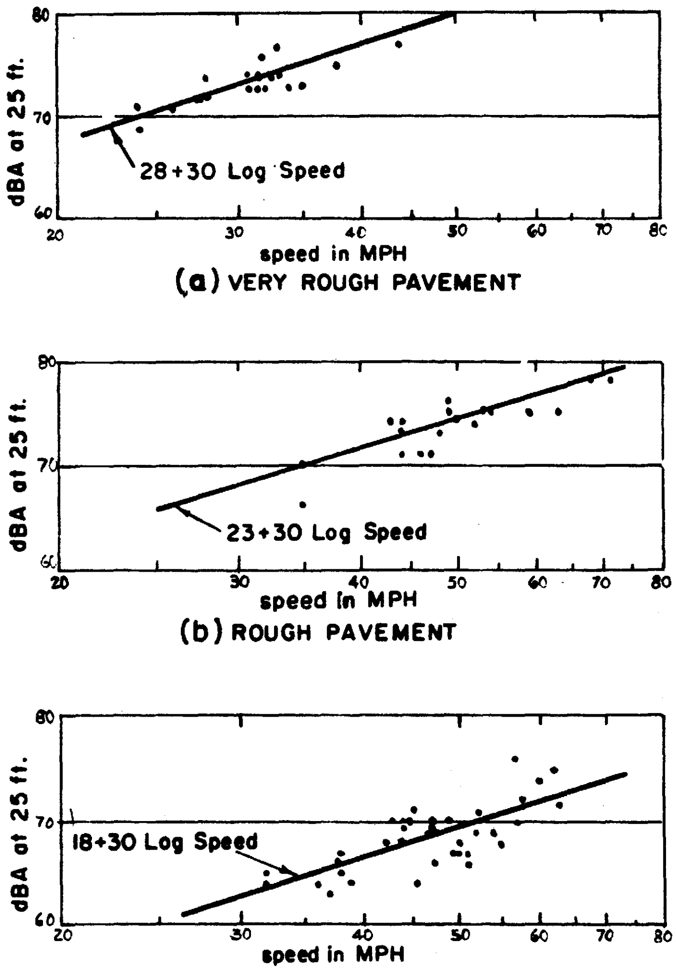

Figure A-3: A-scale noise level in dBA at 25 ft. for passenger cars for random drive-bys on (a) very rough pavement , (b) rough pavement, and (c) very smooth pavement (Source: Reference 11).