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Research on Motor Vehicle Performance Related To Analyses for Transportation Economy

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The need for additional and up-to-date running costs of motor vehicles for use in highway engineering economy studies is stressed in this paper. Suggestions are given on what data are needed and on the research methods that could be used to achieve the desired results. Detailed discussion is given on fuel consumption, tire tread wear, engine oil consumption, maintenance and repair, and depreciation as related to vehicle speed and speed changes, and to highway design factors. Specific fuel consumption curves and detailed running costs for fuel, tires, oil, maintenance, and depreciation are given for a typical passenger car for speeds up to 80 mph on a level tangent highway. Fuel and time consumption curves for speed change cycles are given for a full range of initial speeds for a diesel 2-S2 tractor-semitrailer. The paper concludes that researchers need to plan the whole project of study of motor vehicle cost for economy studies before starting test operations on any one factor, so that all data useful to other phases of study and analysis can be recorded from the very beginning of the research work.

•BEGINNING in the 1920's, research was undertaken on the performance of motor vehicles with respect to highway design. This early research gave major attention to fuel consumption and tractive resistance. Research on tire wear on roadway surfaces followed. In these pioneer days, the research objective was to find monetary values for the factors (mainly fuel consumption) involved in the relative economy of bituminous and concrete pavements as opposed to earth, gravel, or stone surfaced roads.

Research and interest in the economy of highway transportation were quiet from about 1940 to 1950. Part of this relapse was due to the war, and part was due to lack of interest on the part of research individuals, State highway departments, and educational institutions. About 1950, interest began to pick up with studies of the cost of running motor vehicles with respect to certain features of highway design. This renewal of interest was stimulated by the expansion of highway construction, and from the impetus of greater traffic volume and higher travel speed.

Early highway construction, beginning in 1920, was primarily for the purpose of getting an all-weather roadway surface, with little attention to traffic capacity and sustained speed. Later, as traffic volumes became heavier and the mixture of traffic between types of passenger cars and types of freight-carrying vehicles became more widespread, the objective of highway construction was no longer "to get the farmer out of the mud," but to determine the most economical method of serving large volumes of traffic. This change in viewpoint brought attention not only to highway cost, but also to motor vehicle running cost. The objective has been to achieve the lowest cost of transportation—highway cost plus motor vehicle cost.

The whole range of highway design, including geometrics and structural design, and those features which control traffic operation and speed, is subject to the analysis for economy so far as total transportation costs are concerned. With the increase in traf-

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fic and the development of urban congestion, it has become desirable to study minutely the features of highway design as they affect the running cost of motor vehicles.

The introduction of uphill truck lanes, the design of divided highways on a directional basis, the coming of urban expressways, and the adoption of a variety of traffic control devices, all have brought on the desirability of improving the procedure used in studies of the economy of highway design. In addition, the large traffic volumes have made possible large amounts of dollar benefits which now justify features of highway design, whereas previously, these features could not be justified economically because of low traffic volumes. Increase in truck traffic, both in frequency and in vehicle gross weight, has brought about the necessity of studying the effect of minus and plus grades on the cost of operating motor vehicles.

It is desirable that research on the performance of motor vehicles be a continuing research because motor vehicles change in their operating characteristics, performances, and running costs. The high horsepower passenger automobiles of today can negotiate practically any gradient up to 8 percent grade at speeds as high as 60 mph in high gear. On the other hand, there has been introduced to the traffic in recent years the lower horsepower cars, both domestic and foreign, which do not have high top speed or low ratio of weight to horsepower.

It becomes necessary, then, to give more attention to the selection of vehicles on which the running cost should be determined than has been desirable heretofore.

This paper is based primarily on the author's personal study and experiences in the field of the running cost and performance of motor vehicles as viewed from the objectives of economy studies of highway design geometrics and highway location.

A few specific results are presented, but the main objective of this paper is to disclose the shortcomings of existing literature on the performance of motor vehicles with respect to economy of highway design, and to suggest how these shortcomings can be overcome by concentrated, organized research directed to this purpose.

THE PROBLEM

Despite the years of research and testing of the performance of motor vehicles, the literature is still seriously lacking in the effect of highway design and traffic operations on the running cost of motor vehicles. The information for heavy trucks is especially lacking; therefore, a serious analyses in depth to determine just what information is needed, followed by a carefully planned research program to get the desired information is necessary.

Motor Vehicle Running Cost

It is frequently remarked, "Do we not know what it costs to operate motor vehicles?" The answer to the question is yes and no. Commercial operators, particularly the major transport lines, do know overall what it costs them to operate their freight vehicles. Sometimes these companies know the answer for specific kinds of vehicles with respect to axle arrangement or gross vehicle weights, but more particularly, they know their cost only on a fleet basis.

A few owners of passenger cars keep complete operating cost records. They know what it costs them to operate their specific vehicle in overall general usage, but not as affected by highway design. Tables 1 and 2 comprise one such record for a 1949 model car retained in the same ownership during the period of this record.

Tables 1 and 2, however, are accurate records of the overall ownership cost of only one vehicle. These records are probably not representative of the 66 million passenger cars in use. Also, these records are practically worthless when applied to the analysis of economy of highway design. It becomes essential, therefore, to take specific vehicles of known specific characteristics, design elements, and performances and to operate these as test vehicles over specific highways such that the effect on the running cost of the vehicle of each element of highway design can be measured.

Table 3 shows a subdivision of the general maintenance and other cost items for passenger cars. Records of maintenance cost by some such classification are helpful in allocating maintenance cost to speed, speed changes, and grades. The total process

TABLE 1

OPERATING COST OF A 1949 4-DOOR SEDAN[a]

Cost Item	Cost ($)													Cents per mile
	Date													
	Nov.-Dec. 1951	1952	1953	1954	1955	1956	1957	1958[b]	1959	1960	1961	1962	Total	
Mileage														
Body	1.50	7.75	43.54	11.50	14.55	7.39	7.50	5.25	9.30	0.00	1.20	0.00	109.48	0.128
Brakes	0.00	2.25	27.77	0.00	2.25	0.50	61.55	2.50	5.20	18.65	1.00	0.00	121.67	0.142
Chassis	0.00	1.85	32.42	2.75	14.40	16.80	0.00	15.28	0.00	39.45	9.00	0.00	131.95	0.154
Electrical	0.00	25.56	8.25	8.00	26.75	0.00	12.75	0.00	0.00	0.00	0.00	15.95	97.26	0.114
Engine	4.10	17.55	16.47	27.15	14.75	188.20	21.40	7.25	4.35	1.00	4.50	9.20	315.92	0.370
Engine oil	1.80	17.14	20.67	20.87	21.00	12.36	18.27	18.25	7.50	3.60	6.45	9.05	156.96	0.184
Gasoline	27.61	219.55	219.39	240.36	249.78	242.27	290.80	258.97	94.93	108.40	99.37	108.61	2,160.04	2.526
Greasing	4.80	10.75	11.25	9.50	7.25	4.45	5.65	6.05	5.25	2.00	3.00	3.00	72.95	0.085
Power chain	2.05	15.15	1.95	7.05	0.00	40.18	0.00	0.00	1.70	0.00	0.00	0.00	68.08	0.079
Tires	1.50	30.39	46.90	23.56	61.88	2.70	2.00	70.26	0.00	0.50	0.00	0.00	239.69	0.280
Subtotal	43.36	347.94	428.61	350.74	412.61	514.85	419.92	383.81	128.23	173.60	124.52	145.81	3,474.00	4.063
Time														
AAA member	0.00	0.00	0.00	26.00	26.00	26.00	26.00	26.00	26.00	26.00	26.00	26.00	234.00	0.274
Insurance	15.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	110.00	110.00	110.00	110.00	1,085.00	1.269
Licenses	1.83	8.50	8.50	8.50	15.00	15.00	15.00	15.00	18.50	18.50	20.00	20.00	164.33	0.192
Parking	7.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	48.00	48.00	48.00	48.00	493.00	0.577
Tolls	6.10	36.50	36.50	36.50	36.50	36.50	36.50	36.50	36.50	36.50	36.50	36.50	407.60	0.477
Other	-	-	0.50	-	-	0.50	-	0.50	4.50	2.00	1.60	15.55	25.15	0.029
Subtotal	29.93	177.00	177.50	203.00	209.50	210.00	209.50	210.00	243.50	241.00	242.10	256.05	2,409.08	2.818
Total cash	73.29	524.94	606.11	553.74	622.11	724.85	629.42	593.81	371.73	414.60	366.62	401.86	5,883.08	6.881
Depreciation	50.00	380.00	356.00	288.00	176.00	80.00	79.00	41.00	30.00	25.00	25.00	20.00	1,550.00	1.813
Ownership														
Garage	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Interest at 6%	16.55	96.90	82.80	63.30	38.40	20.70	20.40	16.20	12.90	10.50	8.40	6.90	393.95	0.461
Property tax	6.95	50.06	48.30	39.56	28.61	15.52	14.59	11.85	9.44	7.61	6.09	5.00	243.58	0.285
Subtotal	23.50	146.96	131.10	102.86	67.01	36.22	34.99	28.05	22.34	18.11	14.49	11.90	637.53	0.746
Grand total	146.79	1,051.90	1,093.21	944.60	865.12	841.07	743.41	662.86	424.07	457.71	406.11	433.76	8,070.61	9.440

[a]Equipment with 6-cylinder, 116-hp motor, fluid drive, semi-automatic transmission, and 7.60 × 16 tires, purchased Nov. 1951 for $1,650 and sold Dec. 1962 for $100.
[b]Nov. 1958—became a two-car family for remainder of this record.

TABLE 2

BASIC DATA AND SUMMARY OF THE OPERATING COST RECORD GIVEN IN TABLE 1

Date	Odometer Reading Beginning Year	Miles Driven During Year	Market Value Beginning Year ($)	Gasoline Consumed Gal.	Oil Used (qt)	Gasoline Consumption (mi/qt)	Oil Used (mi/qt)	Cost Item (cents/mi)				Total Cents per Mile	Gasoline Cost (cents/mi)	Gasoline Cost (cents/gal)
								Mileage	Time	Depreciation	Ownership			
Nov-Dec 1951	19,719	1,203	1,650	107.2	6	11.22	200.5	3.60	2.49	4.16	1.95	8.04	2.30	25.76
1952	20,922	11,151	1,600	830.4	48	13.42	232.3	3.12	1.59	3.41	1.32	9.44	1.97	26.44
1953	32,073	10,027	1,220	768.8	46	13.04	218.0	4.27	1.77	3.55	1.31	10.90	2.18	28.54
1954	42,100	10,623	864	805.0	47	13.20	226.0	3.30	1.91	2.71	0.97	8.89	2.26	29.86
1955	52,723	11,060	576	846.6	44	13.06	251.3	3.73	1.89	1.59	0.61	7.82	2.26	29.50
1956	63,783	9,678	400	800.5	33	12.09	312.2	5.32	2.17	0.83	0.37	8.69	2.50	30.26
1957	73,461	11,088	320	934.2	31	11.87	357.6	3.79	1.89	0.71	0.32	6.71	2.62	31.12
1958[a]	84,549	9,364	241	860.6	30	10.88	312.1	4.10	2.24	0.44	0.30	7.08	2.76	30.09
1959	93,913	2,750	200	312.2	12	8.81	229.2	4.66	8.85	1.09	0.81	15.41	3.45	30.40
1960	96,663	3,086	170	303.0	6	10.18	514.3	5.62	7.81	0.81	0.59	14.83	3.51	35.77
1961	99,749	2,717	145	314.6	10	8.64	271.7	4.58	8.91	0.92	0.53	14.94	3.65	31.58
1962	102,466	2,749	120	333.1	14	8.25	196.4	5.30	9.31	0.73	0.43	15.95	3.95	32.61
Total or Avg.	-	85,496	-	7,216.2	325	11.85	263.1	4.063	2.818	1.813	0.746	9.440	2.526	29.93

[a]Nov. 1958—became a two-car family for remainder of this record.

necessitates controlled tests of specific vehicles under known highway and traffic conditions, laboratory tests, and an analysis of total operating cost records.

The objective of research for the purpose of providing the necessary information by which the relative economy of proposed highway design factors can be determined, is to relate each of the motor vehicle running cost factors (fuel consumption, tire wear, oil consumption, maintenance and repair cost, depreciation cost, accident cost, and travel time) to each of the highway design and traffic factors (distance, plus grades, minus grades, horizontal curves, roadway surface, speed, and speed changes).

Thus motor vehicle operation on horizontal curves needs to be studied to measure the effects of radius of curve, superelevation, and vehicle speed on the consumption

TABLE 3

CLASSIFICATION OF COST ITEMS FOR MOTOR VEHICLE OPERATING COSTS

Body	Brakes'	Chassis	Electrical	Engine	Engine Oil	Engine Fuel	Greasing and Lubricants	Power Train	Tires	Other	Miscellaneous
Bumpers	Adjusting	Frame	Battery and cables	Air cleaner	-	-	Chassis	Clutch	Balance	Safety inspections	Depreciation
Doors	Cylinders	Front end	Generator and belt	Antifreeze	-	-	Differential	Differential	Chains	Tow-in	Insurance
Heater	Drums	Gas line and tank	Lamps and bulbs	Bug screen	-	-	Universals	Drive shaft	Flats	Radio	Licenses
Instruments	Fluid	Mufller, tail-pipe	Regulator	Carburetor	-	-	Transmission	Transmission	Rotating	Small tools	Tolls
Fenders	Lining	Steering	Starter motor	Distributor	-	-	Fluid drive	Transmission fluid	Snow tires	-	Parking
Glass	Shoes	Wheel and axles	Turn signal	Fuel pump	-	-	Front wheels	Universals	-	-	Accidents
Hub caps	-	-	Wiring	Fan and belt	-	-	Grease fittings	-	-	-	Auto club membership
Interior	-	-	-	Internal work	-	-	-	-	-	-	Garage
Keys, locks	-	-	-	Oil filter	-	-	-	-	-	-	Interest on investment
Paint	-	-	-	Radiator	-	-	-	-	-	-	Personal property tax
Rattles	-	-	-	Spark plugs	-	-	-	-	-	-	-
Wash, polish	-	-	-	Steam clean	-	-	-	-	-	-	-
Windshield wiper	-	-	-	Tuneups and parts	-	-	-	-	-	-	-
-	-	-	-	Water pump	-	-	-	-	-	-	-

of fuel, the wear of tread rubber, the consumption of engine oil, the maintenance and repair of the vehicle, and on the mileage life of the vehicle. In addition, the effect of curvature on accident cost and on travel time needs to be determined to complete the picture.

Consumption of fuel, tires, and engine oil can be measured on the roadway or in the laboratory, such that these elements of performance can be converted to running cost with reasonably reliable results. On the other hand, the maintenance cost of the vehicle and the depreciation cost of the vehicle are difficult to relate to specific elements of highway design. Work is progressing on the study of accident frequency and the cost of accidents, whereby eventually the highway design and traffic operation factors can be fairly reliably related to the cost of motor vehicle accidents. Travel time, of course, is a direct result of vehicular roadway speed. Travel time can be determined by field observation of the traffic speed under different features of highway design; but to place a price on travel time is still a subjective process.

Traffic Performance

To aid the researchers in determining the performance of motor vehicles and their running costs for application to economy studies, it is desirable to make extensive observations of the performance of vehicles in normal traffic. Highways of different lane design, geometric considerations, and traffic volumes should be observed in detail to determine the following factors of the performance of traffic: speed on plus and minus grades for a range up to 8 percent; speed on the horizontal curves of different radii and different superelevations; speed changes in magnitude and frequency under different kinds of driving; brake applications and pressure; braking time duration; and deceleration and acceleration time for stops from a range of initial speeds.

Because vehicle speed is a critical factor in both running cost and travel time, speed distributions are needed under a range of hourly traffic volumes and for 24-hr days, for at least a full week. A few control speed studies are needed for the full year. These speeds could be recorded at the permanent traffic counting stations.

Urban traffic is costly because of the continuously changing speeds and is also difficult to describe in the manner needed to estimate the running cost of vehicles. Instrumentation and recording devices are now available by which speed, speed changes, distance, time, and other factors can be collected by driving test cars in the traffic over a selection of typical urban streets.

METHODOLOGY

There are three methods of research and testing that may be used in developing motor vehicle running costs and performance data necessary for the studies of highway engineering economy. These methods are: (a) driving test vehicles on the highway, (b) laboratory testing, and (c) analysis of the records of the cost and of the use of motor vehicle operation as kept by vehicle owners. By combining these three methods, the desired results can be approached more closely than by using any single method alone.

Use of Test Vehicles

Most past researchers who have used any one of the methods have neglected to see the advantages of combining the three methods. A second neglect has been failure to see that information supplementary to the main objective of a particular test would be highly beneficial to other objectives not a part of the immediate goal. For instance, when measuring fuel and time consumption during speed changes, deceleration and acceleration distances and times have not been generally recorded. Yet these factors are helpful in estimating tire wear, oil consumption, and maintenance costs. Research on grades has been almost wholly limited to plus grades, yet fuel, tire, oil, and maintenance costs on minus grades are equally important. All fuel consumption tests would be more useful if throttle opening, manifold pressure, and engine revolutions per minute were reported. Wheel revolutions per mile in all tests would be helpful in fuel, tire, oil, and maintenance analyses. Other factors could also be mentioned.

Researchers on the cost and performance of vehicles need to outline the whole problem at the outset, so all factors are identified and their interrelation recognized before test work begins. This approach is especially important to testing in the laboratory when road conditions need to be simulated. For instance, a few control tests of fuel consumption and tire wear on horizontal curves can be made in the field. By recording such items as throttle opening, manifold pressure, engine revolutions, wheel revolution, steering angles, slip angles, horsepower at the drive wheels, off tracking, and other factors, the few field tests can be extended to a full range of speeds, radii of curves, and superelevations by laboratory simulated tests. In addition, these data would help in calculating oil consumption and maintenance costs.

The full range of vehicle performance should be conducted with the same test vehicles, both in the field and laboratory. By planning the complete series of tests and observations initially, the most advantageous use can be made of on-the-road and laboratory tests.

Cooperation of Industry

The motor vehicle manufacturers, specialty manufacturers, petroleum companies, and tire companies carry on a large research and development program in connection with the development of new products and improved vehicles. Much of this work, however, is not reported in the literature or much of that reported is not reported in the form usable in developing the necessary vehicular performances for use in the engineering economy studies of highway design.

Inasmuch as these industrial organizations have available the necessary equipment, general facilities, and trained personnel, it is suggested that they might be willing to make certain determinations of vehicular performance for specific use in engineering economy studies. These industries might be willing to undertake both field and laboratory tests for nominal fees, should some central organization, such as the Highway Research Board or the U. S. Bureau of Public Roads, approach them with definite proposals.

The author endeavored to get specific information from these companies with reference to fuel consumption, tire wear, and engine oil consumption. He received good cooperation, but the companies did not have the specific information requested. For example, three tire manufacturing companies indicated that they did not know the specific rates of tread wear for heavy transport vehicles operating at different specific speeds. Likewise, the tire manufacturers were able to give only sketchy information on the rate of tire wear on horizontal curves. Although this subject has been investigated to a certain extent, the data on curvature, superelevation, and speed necessary for economy studies has not been reported.

Petroleum companies through both field operation of vehicles and laboratory tests, have made certain determinations of the rates of consumption of engine oil. Here again, however, the desirable conditions similar to road conditions were not reproduced. The objective of such tests was to compare different oils or to determine certain other characteristics of engine performance or lubricating oil performance other than a rate of consumption under different engine speeds and horsepower outputs.

It might be possible through a more thorough study of the operations of truck transport, to gain some useful information relative to truck performance and running cost than has heretofore been uncovered. This might necessitate the truck transport people keeping some specific records, particularly of fuel consumption, travel speeds, travel times, and tire wear wherein the same vehicle travels the identical route day after day.

Use of the Literature and Cost Records

As previously indicated, the performance of vehicles has been observed and the results reported, beginning in 1920. However, as of today, there is much needed information that cannot be found. Helpful facts, isolated values, testing methods, and comparative factors are to be found in the literature upon careful and extensive search. The references in this paper are illustrative of what is available.

Although the reported cost of operating vehicles in general service does not disclose unit costs that can be associated with specific features of highway design, such costs are helpful for controls and for relative costs. Maintenance cost of vehicles, engine oil changes, and depreciation costs are not measurable in ordinary test running. The basis of allocating these costs to speed, speed changes, grades, and distance must be practice. A good comparison of the effects of rural driving as compared to urban driving could be made by analysis of the complete records of the cost of operation of vehicles driven mainly in these two areas.

DESCRIPTIVE INFORMATION NECESSARY

In determining the performance and running cost of motor vehicles for purposes of engineering economy studies, it should be kept in mind that a full description of the test vehicle and of the operating data should be reported. This information is desirable because of the many variations in vehicular design and performance which affect running costs. One of the objects of reporting detailed information is to make it possible for the performance of one vehicle to be converted reasonably well to the performance of other vehicles. Furthermore, with full information available certain theoretical calculations may be possible as to running cost under conditions which were not measured in the field.

Test Vehicle Information to Be Reported

The test car used on the highway and in the laboratory to measure the consumption of fuel, tire tread rubber, and engine oil, and for determining maintenance and depreciation charges, should have a complete description given of its characteristics. This description would include such items as weight on each wheel, gear ratios, steering ratios, tire sizes, engine revolutions per minute-horsepower curve, specific fuel consumption against revolutions per minute and horsepower output, bore and stroke of the engine, center of gravity, type of front end suspension, gear transmission ratios, speed at which gear ratios shift with automatic transmissions, and many other items. The type of front end suspension is important in connection with analysis of slip angles on horizontal curves.

Table 4 is illustrative of the type of information that should be reported along with all test data.

TABLE 4

DESCRIPTION OF 4-KIP PASSENGER CAR

Curb weight (tare weight), lb	3,500
Maximum rated pay load, lb	900
Gross road weight used in running cost tables, lb	4,000
Gross weight rating, lb	4,400
Gross road weight (cost tables) per net horsepower, lb	18.6
Body type	4-door sedan
Height, ft	4.8
Width, ft	6.5
Length, ft	17.0
Frontal projected area, sq ft	26.0
Wheel base, power unit, ft	9.7
Number of axles	2
Number of wheels	4
Size of tires	7.50 × 14
Ply rating of tires	4
Rear axle ratio	3.92
Transmission gear ratios:	
First	2.78
Second	1.62
Third	1.00
Number of cylinders	8
Bore and stroke, in.	3.625 × 3.66
Displacement, cu in.	302
Type of fuel	Gasoline
Gross horsepower and rpm	187/3800
Net horsepower and rpm	163/3600
Idling speed, rpm	450
Engine oil capacity, qt	5
Cost new, with tires, power unit, $	2,510
Cost, complete set tires (no spare), $	92

Test Information to Be Reported

Reporting full conditions prevailing during the testing of the vehicle on the highway should make it possible to simulate certain of these conditions in the laboratory for measuring fuel consumption, tire wear, and oil consumption. One excellent application in this respect is in determining the fuel consumption on downhill operations. Under certain conditions of downhill operation, the engine may be at low horsepower output or it may produce negative horsepower output when used to brake the forward movement of the vehicle. Under these conditions, the manifold is under a lower pressure; this lower pressure will affect fuel consumption and engine oil consumption.

It is desirable to report at least the following items determined concurrently with measurements of fuel consumption for the highway design factor being considered: roadway speed, horsepower at rear wheels, manifold pressure, throttle opening, engine revolutions per minute and the revolutions per mile of the rear wheels and front wheels, tire pressure and temperature, crankcase temperature; other factors would be altitude, barometric pressure, wind velocity, and air temperature.

RUNNING COST FACTORS

Discussion of factors of running cost is helpful in disclosing possible difficulties and the interrelationship of these factors when testing vehicles.

Measurements of Fuel Consumption

Fuel consumption of a motor vehicle engine is a factor of internal design of the engine, engine speed, engine temperature, gear ratio, gross weight of the vehicle, altitude, air temperature, relative humidity, and other factors. Fuel, however, is a cost element that can be measured and priced, though some difficulty is still being experienced in measuring minute quantities of fuel consumption with the necessary degree of precision. For instance, fuel consumption rates for speed changes (including stops) on horizontal curves and on minus grades are difficult to measure because of the small quantities of fuel consumed in the traveling distance available for the moving vehicle under test conditions.

Figure 1 shows three fuel consumption curves for a 1957 V-8 sedan with a road weight of 4,450 lb. The gallons-per-hour curve has not been used much in economy studies. It is, however, a convenient curve to use in plotting and smoothing field data. It has two main advantages over either the curve for miles per gallon or gallons per mile. The gallons-per-hour curve is concave upward throughout its range, and it may be projected to zero speed to indicate the idling engine fuel consumption.

The two families of fuel consumption curves in Figure 2 are for the same vehicle as for Figure 1. Here the fuel consumption curves in gallons per hour are given for minus and plus grades (-6 to +7 percent). Note that the consumption on the minus grades reaches down to the idling consumption rate when the grade and speed together create the situation that no engine horsepower is required to maintain the road speed. This condition is indicated by the inset curve (straight line) for the floating speed—that

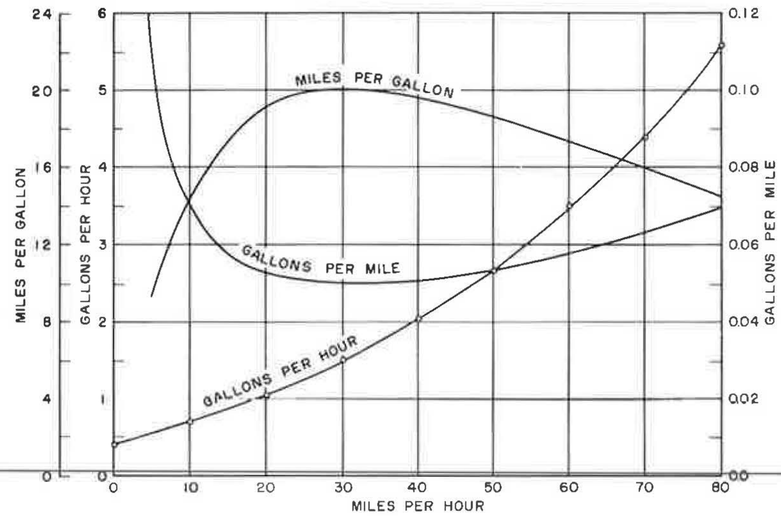

Figure 1. Fuel consumption curves for a 1957 4-door sedan equipped with a V8 engine rated at 230 hp, automatic transmission, and power steering, and weighing 4,450 lb including driver and observer.

downhill speed at which the force of gravity exactly equals the rolling resistance, air resistance, and chassis resistance of the vehicle.

There is some uncertainty whether or not the fuel consumption curves for all plus grades (lower family of curves of Figure 2) intersect at the point of idling fuel consumption at zero speed. The fuel meter used to develop these curves was not sufficiently precise to establish this relationship for certain under the test conditions prevailing.

Tire Tread Wear

Tire tread wear is difficult to measure. Current tires are of high quality and, therefore, it takes thousands of miles to produce enough wear to give reliable measurements. This means that it is difficult to measure tire wear resulting from speed changes or travel around horizontal curves. Here, laboratory tests under simulated conditions should be made.

Tire wear may be measured by determining the depth of tread worn off, or the loss in weight or volume of tread rubber. In most of the researches reported in the literature, tire wear was measured by the depth of tread rubber or by weighing the tire. Each of these methods has certain advantages and disadvantages, but between the two and with the proper research technique, it is possible to get reliable tire wear as affected by the features of highway design and traffic operation.

Generally, the rear wheels and front wheel revolutions per mile have not been reported and temperature and weather conditions may not have been reported. The wheel revolutions per mile are important because of the slippage effect of the wheel under higher speeds or horsepowers which in the end increase the rate of tire wear. Here again, it would be desirable to record the engine revolutions per minute as well as the horsepower at the rear wheels in all measurements of tire wear.

Tire wear on horizontal curves can be as much as one thousand times the rate of wear at the same speed on a level tangent. In operating around the curve, the cornering force developed by both the front tires and rear tires in order to change the direction of travel of the vehicle may become quite high under certain conditions. This high cornering force results in the tires being skidded sideways, which, in effect, subjects the tires to a grinding action as compared to a rolling action when the tires are moving forward longitudinally with the direction of travel.

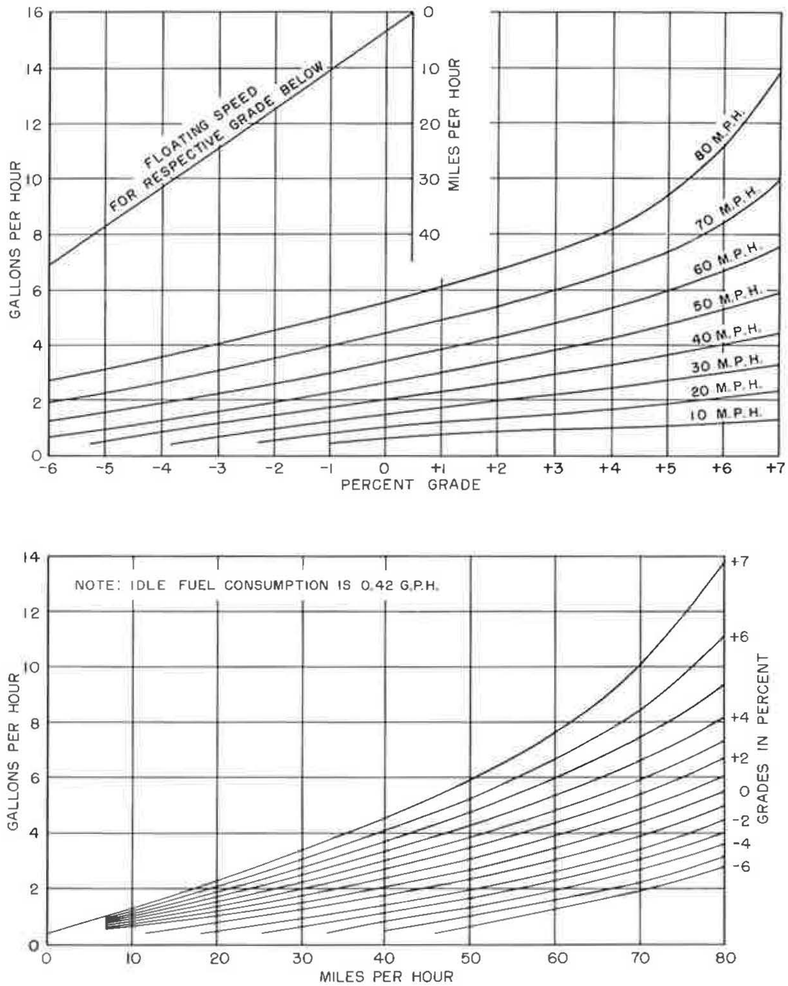

Figure 2. Gallons-per-hour fuel consumption on plus and minus grades for same car as Figure 1. Floating speed is the constant coasting speed maintained going downhill with closed throttle.

The operation of vehicles on horizontal curves should be accompanied by accurate measurements of the steering angle, the superelevation and radius of the curve and the slip angle developed at both the front and rear wheels. This slip angle is the angle of actual travel of the vehicle with respect to the angle it would travel should there be no requirement for understeering or oversteering to negotiate the particular radius of curvature. This oversteering or understeering which causes the development of the slip angle is necessary to create the resisting force necessary to alter the direction of the vehicle.

The slip angle can be zero, positive, or negative depending on whether the superelevation of the curve with reference to the speed of the car is just sufficient to balance the centrifugal force or whether it is deficient or in excess. A negative slip angle would be introduced at slow speed on a highly superelevated curve such that it is necessary to steer away from the center of the curve (against the superelevation) in order to keep the car from slipping down toward the center of the circle. A positive slip angle on a curve is introduced when negotiating the curve at a speed higher than for which it is superelevated. In this case, the cornering force developed by the slip angle is required to turn the vehicle around the curve instead of allowing it to move in the straightforward direction.

Here again, it would be highly beneficial to researchers on tire wear if many different radii and superelevated curves could be driven by a test vehicle which would measure primarily the steering angle, slip angle, horsepower at rear wheels, and the revolutions per mile of each wheel when negotiating curves at different speeds and different superelevations. With this field information at hand, tire wear could be determined in the laboratory under simulated conditions.

The U. S. National Bureau of Standards (85) has done limited work in this area, but the results are not extensive or reported in the form suitable to highway economy studies. Certain of the rubber manufacturers have also done work using laboratory techniques of determining tire wear.

Engine Oil Consumption

Although engine oil is not a major cost item in the running of motor vehicles, it is one item which is possible to measure on a quantitative basis, and thus, reduce unknown costs to known costs.

Engine oil consumption, like tire wear, is not observed in large quantities. It is somewhat difficult to measure for specific elements of highway design. On the other hand, if the performance of the vehicle is fully catalogued at the different conditions of highway design, engine oil consumption can be determined fairly reliably by laboratory test. Certain recent tests of oil consumption have been aided materially in the laboratory by use of isotopes or tracers to determine the relative amount of oil consumption (82).

Engine oil is consumed through a process of oxidation under heat; it is evaporated to a certain extent under heat and pressure; and it is washed down the cylinder walls into the crankcase to disappear through crankcase ventilation. Oil which is forced up into the combustion chamber of the cylinder is burned along with the burning of the engine fuel.

Engine oil consumption varies with manifold pressure, throttle opening, horsepower output, gear ratio, revolutions per minute of the engine, engine temperature, and other factors. The engine under heavy load as compared to light load, generates more heat and operates at a higher temperature, thus inducing more rapid rate of engine oil consumption. At these high temperatures, the engine oil is at a lower viscosity and this thin oil has greater tendency to leak out through joints and bearings as well as to move into the combustion chamber where it is burned. Laboratory testing of engine oil consumption is probably preferable to field testing of engine oil consumption because of the engine hours required to consume enough oil such that measurements of quantity are reliable. On the other hand, there are certain types of current highways, particularly the four-lane divided Interstate or toll highway, in comparatively level country which could be used as check test courses for measurement of engine oil consumption at high speed as well as for fuel and tire consumption.

Engine oil consumption is more a factor of engine speed on a time basis than it is of road speed. As the vehicle engages lower gears in order to develop the required horsepower, the piston travel is more in feet per hour than it is in the higher gears. Oil consumption in the engine is a factor, therefore, of the bore and stroke of the engine and number of revolutions. For these reasons, it is highly desirable that the engine speed in revolutions per minute be recorded simultaneously with a recording of fuel consumption, tire wear, and speed on minus and plus grades.

One of the difficulties in reporting engine oil consumption is how to account for crankcase oil changes. It is one thing to measure lubricating oil consumption during the time the engine is operating, but when it comes to making overall consumption rates meaningful, some consideration must be given to the changing of crankcase oil. Records now available on miles driven per quart of lubricating oil and the number of miles driven per oil change, show a wide variation in practice. Furthermore, the probability is that, even though records of the addition of makeup oil are available on a reliable basis, true consumption of oil while the vehicle is in motion may not be obtained.

This situation could result from the fact that, generally, vehicles will have an oil change when the oil is low rather than when it is up to the full mark. Reported make-up oil then is probably less than the actual oil consumed during the observation period.

In general, lubricating oil is changed at shorter mileage intervals for slow speed and urban driving, where there are many speed changes per mile, than at high speed driving. At high speed, rural type of long distance driving, crankcase oil changes occur at greater mileage intervals because of the more favorable conditions under which the engine is operated. A hot engine keeps itself clean and performs in good function. The fact that the equivalent of a partial oil change is obtained by the addition of a larger amount of makeup oil per mile of high speed driving than is experienced at slow speed driving, is also a factor resulting in high mileage between oil changes.

Maintenance and Repairs

The maintenance and general repair work of the vehicle represents a fairly high percentage of the total cost of operating the vehicle. On the other hand, the allocation of maintenance and repair cost to specific conditions of operation and factors of highway design is most difficult.

The maintenance of the vehicle can be roughly divided into lubricants, the engine, the chassis, the body, the electrical system, and the braking system.

Just how each of these general categories of maintenance of the motor vehicle is affected by highway design and vehicle operation is difficult to determine. However, it is reasonable to expect that the wear and tear on the engine and the electrical system might be somewhat related to either fuel consumption, to horsepower output, or to hours of use, or to all three items. There is general evidence as reported by commercial users that slow speed driving, particularly under a high number of speed changes, is conducive to increasing the maintenance cost of the engine over driving at constant and somewhat higher speeds. A vehicle that is used daily at low speed with a large number of speed changes develops a dirty, gummy engine condition which results in a high amount of mechanical wear and disorder in the engine and lubricating systems. On the other hand, extreme high speed driving generates a greater amount of strain on many parts of the vehicle including higher pressures on bearings and higher general vibration and resisting forces, particularly when changing speeds or changing direction of travel. It is probable that the more moderate speeds (between 30 and 40 mph) produce the minimum rate of wear and tear on the vehicle.

Except for parking, brake wear is wholly attributable to decelerating the vehicle and holding a constant speed on downhill operation. The total cost of brake maintenance can be determined fairly accurately by cost keeping devices. Furthermore, the braking pressures and braking times in vehicular operation on the highway can be measured. It should be possible, therefore, to make a reasonable allocation of the overall expense of maintaining the braking system of a vehicle to the conditions of speed changes of a vehicle on the highway.

There is some evidence that the electrical system providing ignition to the engine wears much more rapidly at high speed than at low speed. The spark plugs and distributor seem not to withstand the higher pressures, temperatures, and rapidity of function as well as they do at lower vehicular speeds.

In some pre-World War II work by Professor Moyer (at that time at the Iowa State University), there is good evidence of the effect on the general maintenance of the vehicle of operations over gravel roads on a year-round basis as compared to operating over bituminous or concrete pavements (54). These measurements of cylinder wear, brake drum wear, and general condition of the car indicate that both the dustiness of operation as well as the amount of vibration and overall strain on the car as a result of rough road surfaces, materially increases the maintenance expense of the vehicle.

Depreciation Expense

Motor vehicles in the long run are relegated to scrap. At this time, or at least at the time they are no longer used on the highway, they can be said to have been fully depreciated. That is, the original cost less their scrap value is wholly chargeable to the operation of the vehicle during its period of life. The depreciation expense could be allocated on a mile basis or on a time basis. Either method will produce comparable results in the end.

On a time basis, however, the vehicle, using market price as an index of depreciation when compared to the cost new, decreases more rapidly in the earlier years of use than it does in subsequent years. The vehicle on the market value basis may reduce to practically scrap value in six or seven years. On a use basis, the passenger cars on the average are maintained in use about twelve years. These figures pertain to passenger cars and light commercial delivery vehicles rather than to the freight transport vehicles. It is known also that passenger cars have a higher average annual mileage when new than they do when they get older. The new vehicles probably are driven an average of 13,000 miles a year the first year of service, and in the last year of service, it might be as low as 3,000 to 4,000 miles.

Regardless of the time element or mileage element, the car ultimately becomes fully depreciated from a cost concept. This depreciation is wholly chargeable to the service rendered by the vehicle. For engineering economy studies, the problem is to find a basis of allocating the depreciation expense of a vehicle to its conditions of operation and use. It is logical to assume that a vehicle driven high annual mileages will in the long run be used a greater total number of miles during its service life than will a vehicle driven low annual mileages. This is because the factor of age of the car affects its desirability of ownership. As a car gets older, newer cars are available which are more attractive to the motoring public and, therefore, in greater demand. New cars are also more reliable than older cars and people will hesitate to buy a really old car for fear of not getting a reliable transportation machine. Using speed as an index to car miles driven in the course of a year, it would be logical to depreciate a car driven at high speed over more total miles of useful life than a car driven at low speed.

And similarly, because of the greater wear and tear on a car under urban conditions of low speed driving, it is reasonable to depreciate the car at a higher rate per mile than it would at the same speed of driving in rural areas.

The conditions of operation conducive to high maintenance and repair cost probably also would result in higher rates of depreciation, all other conditions being equal. After all, only so much maintenance and repair can be done until further repair becomes uneconomical.

The frequency and extent of speed changes and of horizontal resisting forces probably have an effect on the depreciation of the vehicle as well as on the maintenance and repair cost of the vehicle.

Accident Costs

This paper will dispose of accident cost as related to economy studies in two brief sentences. Accident costs are a real road-user cost, the reduction of which could justify much higher highway and traffic control investments. Up to this date, the extensive literature on accident costs and highway safety does not contain a single publication which puts accident costs in the proper light or proper units for application to economy studies.

ILLUSTRATIVE RESULTS

It may be helpful to present two results of the author's work (96) on motor vehicle running cost to illustrate the type of answers desired, in addition to the foregoing curves on fuel consumption (Figs. 1 and 2).

Time and Fuel Consumption with Speed Changes

In the works by Claffey (15) and Sawhill (77) on fuel consumption and time consumption during speed changes, the distance over which the speed change occurred was not recorded. It is, therefore, not possible to determine the rates of acceleration or deceleration from the reported results. It is desirable that the full data be obtained on fuel consumption, time consumption, tire wear, and decelerating and accelerating

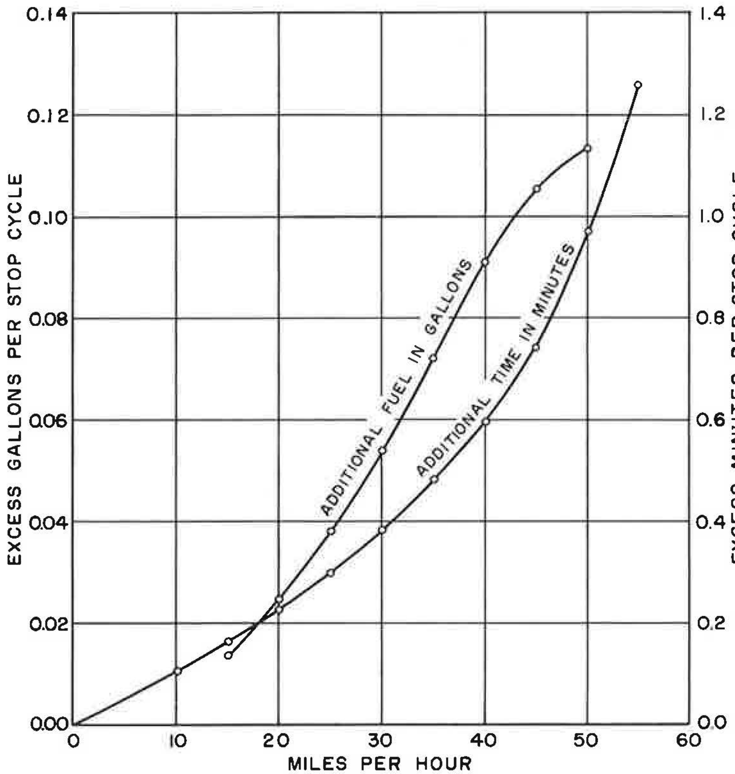

Figure 3. Additional fuel and time consumption over travel at uniform speed for a 2-S2 diesel tractor semi-trailer with a gross weight of 57,800 lb (77).

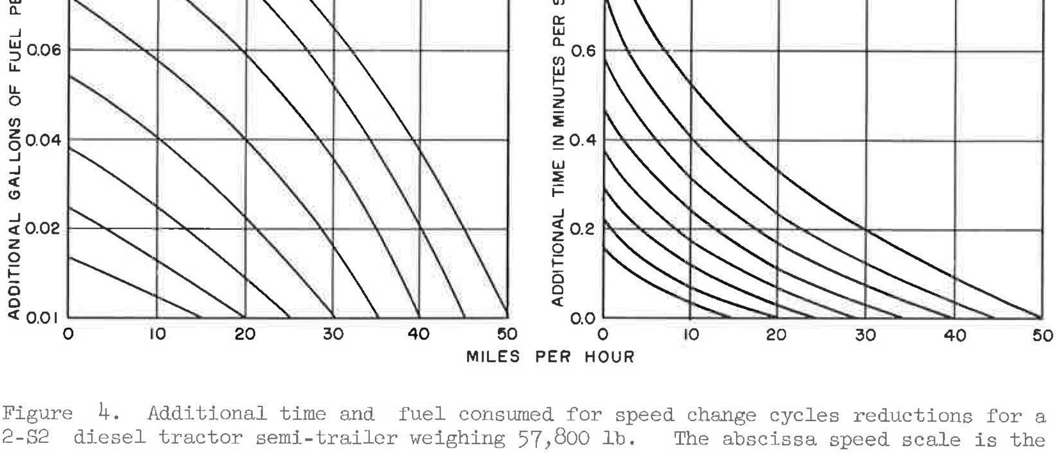

Figure 4. Additional time and fuel consumed for speed change cycles reductions for a 2-S2 diesel tractor semi-trailer weighing 57,800 lb. The abscissa speed scale is the initial speed and the speed returned to for any specific reduction in speed.

TABLE 5

DOLLARS RUNNING COST AT UNIFORM SPEED ON LEVEL TANGENTS BY COST ITEM[a]

Speed (mph)	Running Cost by Item ($)					Total Cost ($)
	Fuel	Tires	Engine Oil	Maintenance	Depreciation	
5	23.55	0.18	4.22	5.38	26.03	59.36
7½	17.50	0.28	3.20	5.43	23.45	49.86
10	14.56	0.38	2.64	5.49	21.86	44.93
12½	12.83	0.49	2.27	5.57	20.66	41.82
15	11.75	0.60	2.03	5.67	19.68	39.73
17½	11.04	0.71	1.86	5.79	18.81	38.21
20	10.56	0.82	1.75	5.93	18.03	37.09
22½	10.21	0.94	1.67	6.09	17.32	36.23
25	10.01	1.06	1.64	6.25	16.67	35.63
27½	9.89	1.19	1.61	6.42	16.08	35.19
30	9.84	1.32	1.60	6.60	15.55	34.91
32½	9.89	1.46	1.59	6.78	15.07	34.79
35	9.96	1.60	1.59	6.97	14.64	34.76
37½	10.10	1.75	1.58	7.16	14.25	34.84
40	10.28	1.90	1.58	7.36	13.91	35.03
42½	10.49	2.06	1.56	7.56	13.60	35.27
45	10.76	2.23	1.55	7.77	13.32	35.63
47½	11.06	2.41	1.52	7.98	13.16	36.13
50	11.41	2.61	1.49	8.19	12.83	36.53
52½	11.80	2.81	1.43	8.41	12.62	37.07
55	12.24	3.03	1.37	8.64	12.43	37.71
57½	12.72	3.27	1.38	8.88	12.25	38.50
60	13.25	3.53	1.48	9.10	12.06	39.42
62½	13.85	3.81	1.50	9.40	11.93	40.49
65	14.51	4.12	1.61	9.69	11.78	41.71
67½	15.25	4.46	1.76	10.01	11.64	43.12
70	16.10	4.85	1.93	10.37	11.51	44.76
72½	17.04	5.30	2.13	10.78	11.38	46.63
75	18.10	5.83	2.36	11.25	11.25	48.79
77½	19.34	6.45	2.64	11.79	11.12	51.34
80	20.79	7.19	2.96	12.41	11.00	54.35

[a]Vehicle; 4-kip passenger car; unit, dollars per 1,000 vehicle-miles; and roadway surface, high type pavement in good condition.

distances for speed change cycles. With full reporting of the distances, times, and rates of speed change, it would be possible to duplicate such performance in the laboratory, and to translate the ultimate results from one condition of operation to another.

For instance, in allocating brake cost to slowdowns and stopping, it would be most helpful to know the braking distance and braking time for each condition of speed reduction and similarly for speed increases.

Each of these gentlemen reported fuel and time consumption for slowdowns of 10 mph from a range of initial speed; Sawhill reported values for a slowdown of 15 mph, also. It is desirable to make field determinations of slowdowns for the full range of travel speeds at 10-mph intervals down to a stop from each initial speed.

Figures 3 and 4 show how diagrams could be plotted from such information. Figure 4 was interpolated for a 57,800-lb 2-S2 tractor semitrailer using the data from Sawhill in which the fuel and time consumed was given for the full stop and for speed reductions of 10 and 15 mph. This generalized figure is applicable to all ranges of speed changes from all initial speeds.

Total Running Cost of a Passenger Car

Table 5 is the computed dollar running cost of a typical passenger car at uniform speed on level tangents by cost item. Gasoline cost is computed at 23 cents a gallon without fuel tax. Comparison tables in the original publication (96) include the running costs on plus and minus grades, horizontal curves, and for speed changes for the following vehicles: 4,000-lb passenger car, 5,000-lb commercial delivery, 12,000-lb single-unit truck, 40,000-lb gasoline powered 2-S2 tractor-semitrailer, and 50,000-lb diesel powered 3-S2 tractor-semitrailer.

This extensive set of tables was prepared by reference to the literature (highly scattered), by personal testing and recordkeeping, by theoretical calculations, and by just plain judgment. Among the striking conclusions resulting from this detailed work was the realization that by prior study and planning of the whole area of the relationship of motor vehicle performance to highway design and to economy studies, the past researchers could have produced much more of the required information at a very small additional cost.

CONCLUSIONS

Concentrated study of the literature on the running cost of motor vehicles as related to highway design and traffic operations reveals the fact that much yet remains to be done through testing of vehicles to produce the desirable results. These desirable results can be achieved by research, but only when the researcher studies the whole problem through and then plans a completer research program to supply each factor. Past researchers have failed to see the entire picture; the result is scattered and uncorrelated bits of information.

Vehicle running costs combined with the heavy volumes of traffic warrant further detailed and complete study because of the high ratio of vehicle cost to highway cost.

Highway economy studies are important to highway design, but they are not fully reliable now because of the lack of reliable information on vehicle running cost.

REFERENCES

1. American Association of State Highway Officials. Road User Benefit Analyses for Highway Improvements--Part 1, Passenger Cars in Rural Areas. Washington, D. C., 1960.
2. Barish, Norman N. Economic Analysis. New York, McGraw-Hill Book Co., 1962.
3. Beakey, John. The Effect of Highway Design on Vehicle Speed and Fuel Consumption. Oregon State Highway Commission, Tech. Bull. No. 5, 1937.
4. Beck, W. An Investigation of Motor Vehicle Parasitic Power Loss by Road Test. M.S. in M.E. thesis, Univ. of Washington, 1962.
5. Bellis, Wesley R. Highway Economics of Benefit-Cost-Ratio Method. New Jersey State Highway Dept: Program of Group Instruction for Field Men, 1st Lecture Series, Paper No. 6, 1947.
6. Bergman, Walter. Theoretical Prediction of the Effect of Traction on Cornering Force. Trans. Soc. Auto. Eng., pp. 614-640, 1961.
7. Bevis, Howard W. The Application of Benefit-Cost-Ratios to an Expressway System. Highway Research Board Proc., Vol. 35, pp. 63-75, 1956.
8. Bevis, Howard W. Automobile Costs. Chicago Area Transit Study Res. News, Vol. 11, No. 18, p. 3, Sept. 27, 1957.
9. Bone, A. J. Travel Time and Gasoline Consumption Studies in Boston. Highway Research Board Proc., Vol. 31, pp. 440-456, 1952.
10. Bone, A. J. Effect of Traffic Delays on Gasoline Consumption. Highway Research Board Proc., Vol. 19, pp. 99-125, 1939.
11. Branham, A. K. Economic Evaluation of Two Indiana Bypasses. Highway Research Board Bull. 67, pp. 1-14, 1953.
12. Bryan, F. R., Neerman, J. C., and Hinsch. Metallic Tracer Method for Determining Lubricant in Engine Exhaust. Trans. Soc. of Auto. Eng., Vol. 69, pp. 204-211, 1961.
13. California Water Resources. Dept. of Investigation of Upper Feather River Basin Develop., Int. Rept. on Eng., Econ. and Financial Feasibility of Initial Units, Bull. No. 59, Sacramento, 1957.
14. Charlesworth, G. Cost-Benefit Analyses. In International Course in Traffic Engineering Reports, Theme III, 1956.
15. Claffey, Paul J. Time and Fuel Consumption for Highway User Benefit Studies. Highway Research Board Bull. 276, pp. 20-34, 1960.
16. Clark, William L., and Sawhill, Roy B. Predicting Fuel and Travel Time Consumption of Motor Transport Vehicles. Univ. of Washington, Traffic and Operations Series, Res. Rept. No. 3A, Jan. 1962.
17. Davidson, William. Tires. Measuring Tire Wear by Radio Active Elements. Think, Vol. 17, No. 8, pp. 25-26, Aug. 1951.
18. De Garmo, E. Paul. Engineering Economy. 3rd Ed., New York, MacMillan Co., 1960.
19. Dunman, Robie. Economic Costs of Motor Vehicle Accidents of Different Types. Public Roads, Vol. 30, No. 2, pp. 40-44, June 1958; Highway Research Board Bull. 208, pp. 16-28, 1959.
20. Dykes, P. K. Oil Loss Past Piston Rings. Scientific Lubrication, Vol. 9, No. 2, pp. 11-14, 42, Feb. 1947.
21. Eckstein, Otto. Water Resource Development. Cambridge, Mass., Harvard Univ. Press, 1958.
22. Everett, H. A., and Stewart, F. C. Performance Tests of Lubricating Oils in Automobile Engines. Penn. State College, Eng. Exp. Sta., Bull. 44, 1935.
23. Factors Affecting Tire Mileage. Commercial Car Jour., Vol. 81, No. 2, pp. 120-121, April 1951.
24. Firey, J. C., and Peterson, E. W. An Analysis of Speed Changes for Large Transport Trucks. Highway Research Board Bull. 334, pp. 1-26, 1962.

25. Firey, J. C., and Sawhill, Roy B. Effects of the Tire Pressure and Temperature on the Rolling Resistance of Trucks. Univ. of Washington, Traffic and Operations Series, Res. Rept. No. 4, June 1962.
26. Flynne, H., and Kyropoulos, P. Truck Aerodynamics. SAE Preprint No. 284A, Jan. 1961.
27. Fraser, D., Klingel, A. R., and Tupa, R. C. Friction and Consumption Characteristics of Motor Oils. Ind. Eng. Chem., Vol. 45, No. 10, pp. 2336-2342, Oct. 1953.
28. Gallagher, Gerald. At What Point Do Oil Changes Pay Off For You. Fleet Owner, Vol. 54, No. 12, pp. 74, 76, 78, 80, Dec. 1959.
29. Gelinas, L. P., and Storey, E. B. A Towing Device for Estimating Road Wear. Proc. Internat. Rubber Conf., Washington, D. C., pp. 95-103, Nov. 8-13, 1959.
30. Geddie, George. Longer Lubrication Intervals With This Type of Filter System. Fleet Owner, Vol. 514, No. 4, pp. 64-65, April 1959.
31. Georgi, Carl W. Road Tests on Oil Consumption. Motor Oils and Lubrication, pp. 289-297, Jan. 1950.
32. Giffin, H. W. Some Observations on the Value of Time Saved to Motorists. Highway Research Board Proc., Vol. 28, pp. 53-56, 1948.
33. Glaze, C. K., and Van Mieghem, George. Washington Motor Vehicle Operating Cost Survey. Highway Research Board Proc., Vol. 36, pp. 51-63, 1957.
34. Gough, V. E. Cornering Can Wear Tires Rapidly. SAE Jour., Vol. 64, No. 1, pp. 27-29, Jan. 1956.
35. Grant, Eugene L., and Ireson, W. Grant. Principles of Engineering Economy. 4th Ed. New York, Ronald Press Co., 1960.
36. Geesink, H. A. O. W., and Pratt, C. P. Wear on Passenger Car Tires. Rubber Chem. and Tech., Vol. 31, No. 1, pp. 166-184, Jan.-March, 1958.
37. Gough, V. E., and Shearer, G. E. Front End Suspension and Tire Wear. Proc. Inst. Mech. Eng., Auto. Div. (6), pp. 171-193, 1955-1956.
38. Haney, Dan G. The Value of Travel Time for Passenger Cars: A Preliminary Study. Stanford Res. Inst., Menlo Park, Calif., Jan. 1963.
39. Haney, Dan G. Use of Two Concepts of the Value of Time. Highway Research Record No. 12, pp. 1-18, 1963.
40. Hershey, M. P. Tire Degradation is Accelerated by Modern High Speed Driving. SAE Jour., Vol. 65, No. 8, pp. 85-86, July 1957.
41. Hoch, Irving. Accident Experience: Comparing Expressways and Arterials. Chicago Area Transportation Study No. 13, Dec. 1959.
42. Hoerner, S. F. Fluid Dynamic Drag. Pp. 12-1—12-9. Midland Park, N. J., 1958.
43. Kent, Malcolm F. Fuel and Time Consumption Rates for Trucks in Freight Service. Highway Research Board Bull. 276, pp. 1-19, 1960.
44. Krutilla, John V., and Eckstein, Otto. Multiple Purpose River Development. Baltimore, Johns Hopkins Press, 1958.
45. Kuhn, Tillo E. Public Enterprise Economics and Transport Problems. Berkeley and Los Angeles, Univ. of California Press, 1962.
46. Lane, Paul S. Controlling Oil Consumption in Passenger Car Engines. SAE Jour., Vol. 58, No. 11, pp. 18-22, Nov. 1950.
47. Lay, W. E. Bibliography of Tractive Resistance and Allied Problems. Highway Research Board, Proc., Vol. 19, pp. 50-67, 1939.
48. Locklin, David P. Economics of Transportation. 4th Ed. Homewood, Ill., R. D. Irwin, 1954.
49. Masani, M. R., and Shasrti, Lar Babadur. Indian Roads Transport and Development Association. Ind. Concrete Jour., Vol. 27, No. 12, pp. 437-442, Dec. 15, 1953.
50. May, A. D. Jr. Economics of Operation on Limited-Access Highways. Highway Research Board Bull. 107, pp. 49-62, 1955.
51. McCuen, C. L. Economic Relationship of Engine-Fuel Research. Presented at Mid-year Meeting, Amer. Petroleum Inst., Tulsa, Okla., May 1951.

52. McCullough, C. B., and Beakey, John. The Economics of Highway Planning. Oregon State Highway Dept., Tech. Bull. No. 7, 1938.
53. Moyer, R. A. Skidding Characteristics of Automobile Tires on Roadway Surfaces and Their Relation to Highway Safety. Iowa Eng. Exper. Sta., Bull. 120, 1934.
54. Moyer, R. A. Motor Vehicle Operation Costs and Related Characteristics on Untreated Gravel and Portland Cement Concrete Road Surfaces. Highway Research Board Proc., Vol. 19, pp. 69-98, 1939.
55. Moyer, Ralph A., and Jones, John Hugh. Supplementary Notes and Typical Problems for the Highway Engineering Course (Syllabus X L). Berkeley, Univ. of California Press, 1958.
56. Moyer, R. A., and Tesdall, Glen L. Tire Wear and Cost on Selected Roadway Surfaces. Iowa State College Eng. Exper. Sta., Bull. 161, 1945.
57. New York State Thruway Authority. Substantial Operating and Maintenance Savings and Other Benefits that Accrue to Trucking Firms Using N. Y. State Thruway. Press Release 58-24, 1958.
58. Nordeen, Donald L., and Cortese, Anthony D. Force and Moment Characteristics of Rolling Tires. SAE Preprint No. 713A, June 10-14, 1963.
59. Nothstine, J. R., and Beauvais, F. N. Laboratory Determination of Tire Forces. SAE Preprint No. 713B, June 10-14, 1963.
60. Oglesby, C. H., and Grant, E. L. Economic Analysis—The Fundamental Approach to Decisions in Highway Planning and Design. Highway Research Board Proc., Vol. 37, pp. 45-57, 1958.
61. Oppermann, Paul. The Real Cost of Driving to Work. Mass Transportation, Vol. 47, No. 8, pp. 33-43, Aug. 1951.
62. Patterson, J. K., and Gregor, R. C. Lubrication Factors Affecting Passenger Car Oil Consumption. SAE Reprint No. 252, Nat. Fuels and Lubricants Meeting, Cleveland, Nov. 1957.
63. Patterson, J. K., and Gregor, R. C. Oil Consumption in Automobiles Can Be Predicted. SAE Jour., Vol. 66, No. 4, pp. 63-64, April 1958.
64. Pontius, R. L. Determining Wear in Automotive Engines. Lubrication Eng., Vol. 15, No. 3, pp. 110-115, 118, March 1959.
65. Powell, William S. Accurate Method for Determining Oil Consumption. Automotive Ind., Vol. 98, No. 3, pp. 35, 84, 88-90, Feb. 1, 1948.
66. Radt, H. S., Jr., and Milliken, W. F., Jr. Motions of Skidding Automobiles. SAE Summer Meeting, Chicago, Ill., June 1960.
67. Richey, G. G., Mandel, J., and Stiehler, R. D. An Indoor Tester for Measuring Tire Tread Wear. Int. Rubber Conf., Proc., pp. 104-110, Nov. 8-13, 1959.
68. Riehl, T. A. Treadwear Life Down 18 Percent. SAE Jour., Vol. 66, No. 6, pp. 56-57, June 1958.
69. Roberts, G. B. Power Wastage in Tires. Int. Rubber Conf., Proc., pp. 57-72, Nov. 8-13, 1959.
70. Saal, Carl C. An Evaluation of Factors Used to Compute Truck Performance. Soc. of Auto. Eng., Quarterly Trans., Vol. 3, No. 2, pp. 125-228, April 1949.
71. Saal, Carl. Time and Gasoline Consumption in Motor Truck Operation as Affected by the Weight and Power of Vehicles and the Rise and Fall in Highways. Highway Research Board Res. Rept. 9-A, 1950.
72. Saal, Carl. Performance—Actual vs Computed. Soc. of Auto. Eng., Quarterly Trans., Vol. 5, No. 1, pp. 19-25, Jan. 1951.
73. Saal, Carl C. Operation Characteristics of a Passenger Car on Selected Routes. Highway Research Board Bull. 107, pp. 1-35, 1955.
74. Saal, Carl C., and Petring, F. William. At What Point Does High Horsepower Cease to be Practical in Transport Operations? SAE Nat. West Coast Meeting Portland, Ore., Aug. 1961.
75. Sawhill, Roy B. Fuel Consumption of Transport Vehicles on Horizontal Curves. Univ. of Washington, Traffic and Operation Series, Res. Rept. No. 5, June 1962.
76. Sawhill, Roy B. Fuel Consumption of Transport Vehicles on Grades. Univ. of Washington, Traffic and Operations Series, Res. Rept. No. 6, June 1962.

77. Sawhill, Roy B., and Firey, Joseph C. Motor Transport Fuel Consumption Rates and Travel Time. Highway Research Board Bull. 276, pp. 35-91, 1960.
78. Sawhill, R. B., and Firey, J. C. Predicting Fuel Consumption and Travel Time of Motor Transport Vehicles. Highway Research Board Bull. 334, pp. 27-46, 1962.
79. Schick, Jack M. Economic Analysis of the Congress Street Highway. Ill. Highway Eng., 2nd Quarter, pp. 2-5, 12, 1954.
80. Sprowls, G. M. Impediments to Tire Longevity. SAE Jour., Vol. 58, No. 11, pp. 40-43, Nov. 1950.
81. Stamm, A. F., and Lamb, E. P. Predicting Road Performance of Commercial Vehicles. Soc. of Auto. Eng., Quarterly Trans., Vol. 4, No. 2, pp. 147-160, April 1950.
82. Starkman, E. S. A Radioactive Tracer Study of Lubricating Oil Consumption. Soc. of Auto. Eng., Trans., Vol. 69, pp. 86-100, 1961.
83. Stechert, Dietrich G., and Bolt, Thomas D. Evaluation of Treadwear. Anal. Chem., Vol. 23, No. 11, pp. 1641-1646, Nov. 1951.
84. Line-Haul Trucking Costs in Relation to Vehicle Gross Weights. Highway Research Board Bull. 301, 1961.
85. Stiehler, R. D., Steel, M. N., Richey, G. G., Mandel, J., and Hobbs, R. H. Power Loss and Operating Temperature of Tires. Jour. Res. Nat. Bureau of Standards, 64C, No. 1, pp. 1-10, Jan.-March 1960; Int. Rubber Conf., Washington, D. C., Nov. 8-13, 1959.
86. Stiehler, R. D. Factors Influencing the Road Wear of Tires. Engineering, Vol. 173, No. 4490, pp. 218-222, Feb. 15, 1952.
87. Society of Automotive Engineers. Truck Ability Prediction Procedure. SAE TR-82, 1957.
88. Taberek, Jeroslav J. Mechanics of Vehicles. Mach. Des., 1957.
89. Taylor, C. Fayette, and Taylor, Edward S. Lubricating and Oils, In The Internal Combustion Engine, Rev. Ed., pp. 206-221. Scranton, Pa., Int. Textbook, 1948.
90. Tucker, Harry, and Leager, Marc C. Highway Economics. Scranton, Pa., Int. Textbook Co., 1942.
91. U. S. General Services Administration, Motor Equipment Management Div. Annual Motor Vehicle Report for the Fiscal Year Ending June 30, 1962. Jan. 1963.
92. U. S. Federal Inter-Agency River Basin Comm., Sub-Comm. on Evaluation Standards. Proposed Practices for Economic Analysis of River Basin Projects. Washington, D. C., U. S. Govt. Print. Office, May 1958.
93. Vaswani, Ram. The Value of Transit Time in Highway Planning. Highway Research Board Proc., Vol. 37, pp. 58-71, 1958.
94. Washington State Highway Commission. Washington Motor Vehicle Operating Cost Survey. 1952-1953.
95. Why Tires Wear Faster on Curves. Commercial Car Jour., Vol. 61, No. 5, pp. 43, 87, July 1946.
96. Winfrey, Robley. Motor Vehicle Running Costs for Highway Engineering Economy Studies. Arlington, Va., 1963.
97. Wolf, H. R. Crankcase Oils for Heavy Duty Service. SAE Jour., 48, No. 4, pp. 128-137, April 1941.
98. Zettel, Richard M. Highway Benefit and Cost Analysis as an Aid to Investment Decision. Univ. of California, Inst. of Transportation and Traffic Eng., Reprint No. 49, 1956.
99. Zettel, Richard M. Highway Benefits and the Cost Allocation Problem. AASHO, Proc., pp. 25-38, 1957.

Link Analysis for Route Location

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•THE IMPORTANCE of transportation systems, particularly highways, to the development and continued growth of a region is widely recognized. The transportation engineer in his role as planner and designer of regional transport facilities is primarily concerned with the allocation of available resources in order to obtain the best such system. Such a problem is difficult to solve, yet a rational and well informed society cannot afford to leave the solution to pure chance.

Much work has been done in the Civil Engineering Systems Laboratory at M.I.T. to develop new techniques and computer-oriented analysis methods for use in the location, design and economic analysis of highway systems. This paper illustrates the use of some of these new tools in the location analysis of a short segment of new interstate highway in eastern Massachusetts. The project was undertaken primarily to aid in the further development and testing of these recent developments, and in every phase of the project an attempt was made to use the most modern techniques and methods of analysis available.

The purpose of this paper is to present the most significant findings of this study, as follows: (a) develops the decision-making scheme so that certain interrelationships between the various cost-producing variables of the highway link location problem are clearly indicated; (b) demonstrates methods of maximizing computer utilization in the performance of economic analyses for the location and preliminary engineering design of highway links; (c) describes some of the computer models and data presentation techniques that are available for use in these analyses; and (d) presents recently developed methods of dealing with the uncertainty inherent in transportation systems problems.

Description of Sample Problem

The Interstate and Defense Highway System for the New England area radiates from Massachusetts, with Boston as the focal point. I-495, a major component of this system, is to be a circumferential route around Boston about 16 miles farther out than Route 128. This outer cordon will start near Lawrence, circle through Marlboro and Milford, and terminate at I-95 near Foxboro (Fig. 1). This project is concerned specifically with a 7-mi portion located near the town of Franklin (Fig. 5).

Some of the characteristics of the overall road network of eastern Massachusetts are of interest. The basic system is composed of major traffic-contributing nodes. In addition to the major system of links, there is a rather sizable minor system of highly interconnected local roads and streets (Fig. 1). This "subsystem" serves as both a collector and a distributor of traffic to the major system. The decision to build each individual link of this outer cordon route should be based on the future effect which that link will have on the operation of the entire system, both major and minor. It may, therefore, be decided that one or more links are not feasible or that they should be staged to correspond to the local demands for highway improvement. Because of systems or "network" effects this can only be decided by analyzing the system as a whole. Although mathematical programming and systems analysis techniques appear promising, this analysis must presently be done using traffic prediction and assignment techniques and computing user cost and construction costs on each affected link for every alternative under consideration.

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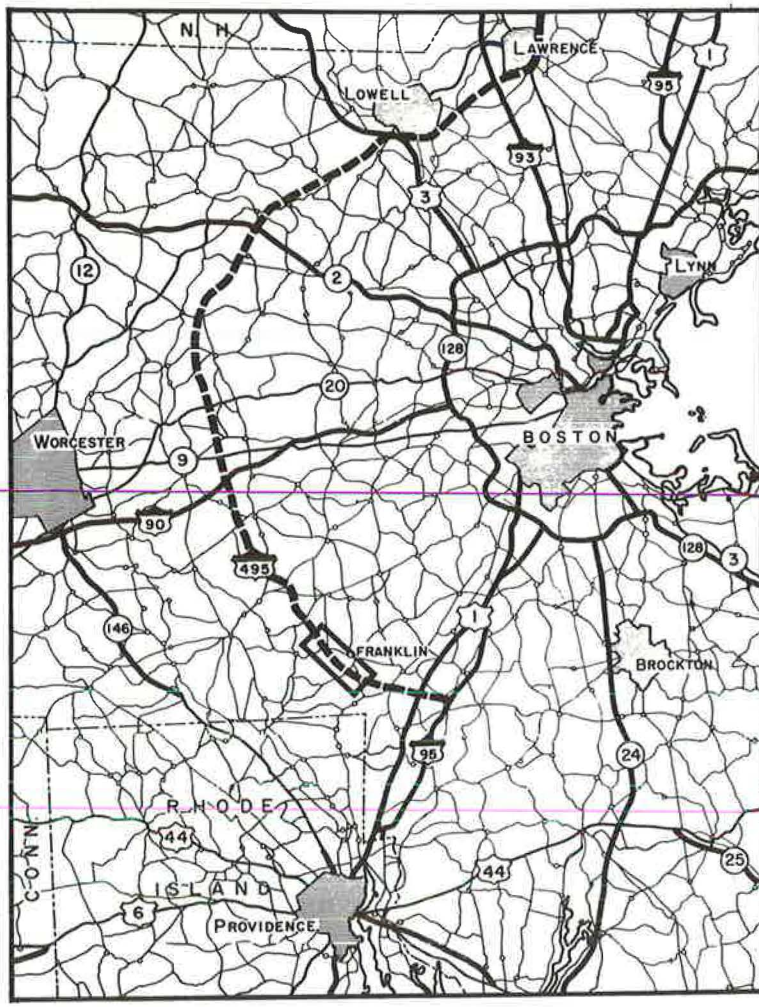


Figure 1. Road system serving eastern Massachusetts.

The decision to build any one link of a highway system is an extremely important one and one in which some present day work is being done and more is needed. However, this is not the problem with which this paper is concerned. The problem studied here is rather one of "link design." The decision to build this particular link, and for that matter each of the links making up I-495, has already been made. The effect which building this link has on the operating characteristics of the entire system should have been considered earlier. The economic, social, aesthetic, and political impact of each major link and its feedback effect on traffic generation must be considered in the macro system problem. In the more micro problem under examination here, traffic volumes, along with such subjective items as social and political impacts and indirect economic benefits, have been assumed to be equal on each of the alternative alignments.

It should also be noted that since this is primarily a suboptimization problem, there is no "null alternative" in the usual sense of the term. The "do nothing" possibility has already been decided against in the regional highway or macro system plan. To make the decision in this suboptimization study, to use an existing local alternative, or to build an entirely new road would be incorrect as no local alternative exists at this decision level.

The Highway Engineering Process

The process of engineering can be viewed as being essentially one of hierarchical decision making; each level of the hierarchy involving operations upon information to produce a selected course of action (1). These operations take the form of identifying goals and decision criteria, searching for a set of alternatives, predicting the physical consequences of each alternative, evaluating these consequences according to a value scheme, and deciding on the basis of the decision criteria to accept either an existing alternative or to continue the search process. In the solution of an engineering problem, these basic operations are repeated at each of the "levels" of analysis.

Examination of the transport system location and design problem indicates that it fits this hierarchical structure. Typical of the higher levels of analysis are decisions as to what areas the system should serve. Somewhat lower decision levels are concerned with the planning of specific projects and with the preliminary location of individual links within bands of interest. The lowest levels of the hierarchy are represented by preliminary engineering design and by the preparation of design plans and specifications. Each of these levels can be broken down into the five engineering processes: identification of goals, search for alternatives, prediction of consequences, evaluation, and decision. Regardless of the exact hierarchical structure, it is clear the entire location and design process involves an extremely large number of alternative courses of action. It is the purpose of engineering research to increase the ability of the engineer to make good decisions at each level of analysis.

Method of Approach to the Location Decision

In any engineering decision-making scheme which has as its purpose the rank ordering of alternatives, it is desirable that the alternatives be clearly defined (2). More is implied in this statement than merely a clear spatial definition. More precisely, each alternative should be defined in some detail according to its economic, social, aesthetic, and political consequences (3). Of these four, economic consequences have probably received the most emphasis in recent years. A variety of reasons can be stated for this. Profound changes in the economic activity level of areas surrounding many new, controlled-access highways have called special attention to this factor. Moreover, social, political, and aesthetic impact are intangible and consequently hard to define in objective terms. Also, some feel that these other types of impact can be expressed in economic terms alone. For these and other reasons, social, political, and aesthetic factors have frequently been slighted or ignored completely. This can be extremely dangerous. For urban areas and for rapidly developing regions, the social and political aspects of a location may frequently govern the decision, with economic considerations playing a lesser role. Aesthetic values, or the "view from the road" concept, are also beginning to be of greater importance, especially in scenic or historic areas.

Grant advocates that economic analysis be given a respectable, yet not overbearing role: he states that in comparing investment alternatives, it is desirable to make the consequences commensurable with investments (4). At the same time, he makes allowance for the effect which other types of impact will have on the decision-making process. He adds that decisions among investment alternatives should give weight to any expected difference in consequences that have not been reduced to money terms. In other words, the "dollar" answers from an economic study do not dictate a final decision. However, they do provide a money figure against which other types of impact can be weighed, thereby decreasing the uncertainty with which the engineer-decision maker is faced. Following this general approach, a study will consist of identifying all of the relevant cost-producing variables in the particular problem under investigation and then measuring the costs associated with these variables for each of the alternate alignments using computer models where appropriate. The costs for each alignment can then be combined either by hand or by a computer program into a single measure of effectiveness. The most easily used measure of goal achievement is total annual cost, although benefit-cost ratio, present worth, or rate of return are also satisfactory when used correctly.[1] The sensitivity of this measure of effectiveness to changes in the value of the various cost-producing variables and to other types of impact should then be examined.

If costs for an alternative are to be combined into a single measure, it is common to use one interest rate, one value of project life, one estimate of projected future traffic volumes, one estimate of user time costs, and one set of assumed salvage values. However, a decision is very much a function of the above parameters and will change as the above values are varied (5). For example, the rank ordering of alignments may be completely different with an interest rate of 11 percent from the way it was using a rate of 6 percent. The same computer program used to calculate measures of effectiveness for the project described herein was written so that the sensitivity of the decision to changes in the previously mentioned variables could be examined. By finding out at what values this rank ordering changes and how sensitive this ordering is to change, the engineer can select a most probable range of parameter values for his economic decision model rather than just a single value.

Development of Economic Equations

The mathematical description of the equations used for the evaluation of the alternative highway alignments is outlined. The variables used in the annual cost criterion function are defined, and it will be shown in subsequent sections how estimates of the values for some of these variables can be obtained. It is assumed that the same number of trips are taken on each of the routes under consideration. Since this is the usual condition for a typical link analysis, the effects of induced traffic can be neglected.

The computation of annual cost for each alignment is based on the following equation relating initial capital costs, user time and operating costs, and maintenance costs (6, 7):

$$TAC = ACC + AUC + AMC \tag{1}$$

where

TAC = total annual cost ($),
ACC = annual capital cost ($),
AUC = annual user cost ($), and
AMC = annual maintenance cost ($).

Each of these three components of annual cost can be further broken down. Annual capital cost becomes:

$$ACC = (tcc) \times (CRF) \tag{2}$$

where

tcc = total construction cost ($), and
CRF = capital recovery factor.

$$tcc = ec + sc + pc + dc + ic + rc + lc \tag{3}$$

where

ec = earthwork cost ($),
sc = structures cost ($),
pc = pavement cost ($),

[1] It is the purpose of this paper to demonstrate methods of estimating consequences and not to compare the different measures of effectiveness commonly employed in economic analyses.

dc = drainage cost ($),
ic = interchange cost ($),
rc = relocation cost ($), and
lc = land and right-of-way cost ($).

$$CRF = \frac{i\,(1 + i)^n}{(1 + i)^n - 1} \tag{4}$$

where

i = interest rate per interest period ($), and
n = service life (years).

This relation for annual construction cost holds only for the simple case where the service lives of the various components are the same and where there is no salvage value. Where this additional refinement is justified, and it frequently is, the annual construction cost is the sum of the individual components:

$$ACC = \sum_{k=1}^{j} CRF_k \times \left[cc_k + \left(sv_k \times PWF_k \right) \right] \tag{5}$$

where

j = total number of construction cost categories,
k = category presently being considered,
CRF_k = capital recovery factor for the appropriate life,
cc_k = construction cost category under consideration,
sv_k = salvage value of this construction cost category, and
PWF_k = present worth factor for the appropriate life.

where

$$PWF = \frac{i}{(1 + i)^n - 1} \tag{6}$$

Annual user cost becomes:

$$AUC = (EAT) \times (doc + utc) \tag{7}$$

where

EAT = equivalent annual traffic (vehicles/year),
doc = direct operating cost ($/vehicle), and
utc = user time cost ($/vehicle).

These can be further broken down as:

$$EAT = vol + av + \frac{av}{1} - \frac{(n) \times (av)}{1} (CRF - i) \tag{8}$$

where

vol = present annual traffic volume (vehicles/year), and
av = annual numerical increase in traffic volume (vehicles/year/year).

Direct operating cost is

$$doc = \sum_{i=1}^{j} \left[k_i \times \left(fc_i + trc_i + oc_i + mtc_i + dpc_i \right) \right] \tag{9}$$

where

j = total number of vehicle classes,

k_i = percentage of vehicles of class i,

fc_i = fuel cost of a class i vehicle ($/vehicle),

trc_i = tire cost of a class i vehicle ($/vehicle),

oc_i = oil cost of a class i vehicle ($/vehicle),

mtc_i = maintenance cost of a class i vehicle ($/vehicle), and

dpc_i = depreciation cost of a class i vehicle ($/vehicle).

For time cost:

$$utc = \sum_{i=1}^{j} \left[k_i \times \left(t_i \times tc_i + tur_i \right) \right] \tag{10}$$

where

t_i = time for a class i vehicle to travel alignment (hours),

tc_i = time cost for a class i vehicle ($/hour), and

tur_i = cost of time unreliability for a class i vehicle ($).

In cases where the assumption of a linear growth of traffic cannot be made, user operating and time costs may be computed for each individual year, then discounted to the present time and converted into an annual cost as follows:

$$AUC = CRF \times \sum_{i=1}^{n} atv_i \times (doc_i + utc_i) \times PWF_i \tag{11}$$

where

atv_i = annual traffic volume during year i,

doc_i = direct operating cost during year i,

utc_i = user time cost during year i, and

PWF_i = present worth factor for year i.

Maintenance costs, the third of the major components of annual cost, become:

$$AMC = (mi) \times (mc) \tag{12}$$

where

mi = length of alignment (miles), and
mc = equivalent annual maintenance cost of an alternative ($/mile).

Eqs. 2, 3, 7, 9, 10, and 12 can now be combined into a single equation for total annual cost:

$$TAC = CRF \times (cc + sc + pc + dc + ic + rc + lc) + EAT \times \sum_{i=1}^{j} k_i \times \left(fc_i + trc_i + oc_i + mtc_i + dpc_i + (t_i) \times (tc_i) \times tur_i\right) + (mi) \times (mc) \tag{13}$$

Note again that these equations are based on the assumption that the number of trips between each origin and destination is the same for all alternatives being compared. If one link induces more travel than another, the equations no longer hold and must be modified to reflect the influence of induced traffic. Another assumption implicit in these relations is that systems effects have all been accounted for within the portion of the system under direct study. Important changes in a transportation network frequently have effects which are widely diffused throughout the network. Needless to say these must all be accounted for in order to produce correct results.

It is recognized that such variables as driver comfort and convenience and accident costs are ignored in the foregoing equations. Variables of this type could best be accounted for through use of a sensitivity analysis program. If by ignoring these variables, line J is better than line K, the cost of line J can be increased until line J is no longer better than line K. The amount of increased cost necessary to change the decision gives a measure of the implicit value that would be placed on comfort and convenience or driver safety if line K were originally chosen over line J. In this particular study, it was assumed that no significant differences in levels of service existed between the alignment choices. For this reason, no effort was made to place a quantitative value on either comfort and convenience or driver safety.

Mathematical Models and Computer Programming Systems Employed

A value for each of the cost-producing variables detailed in the previous section was obtained for each alternative alignment using mathematical models. Most were involved enough to require the use of individual computer programs, written specifically for the cost variable or variables under consideration. However, some variables (notably land cost and such vehicle operating costs as oil and tires) were obtained from simple formulas and tables. This was done, not because they do not merit greater sophistication, but because better models were not available.

Basic to the evaluation of costs for each alternative alignment is the determination of the spatial location of the alignment and its associated physical consequences. This role was filled by the DTM Location and Design Systems. In addition to their primary roles of location and prediction, these systems, by furnishing input to the other cost models, served as the basis of the entire study, from alignment selection to final drafting. The specific mathematical models that were used to evaluate each of the cost-producing variables are given in Table 1.

Organizational Conduct of Study

It was evident at the outset of the project that good planning was essential if all work were to be completed on schedule. A relatively small amount of time had been

TABLE 1

TABLE OF MATHEMATICAL MODELS

Variable	Symbol	Mathematical Model
Earthwork cost	ec	DTM design system
Structures costs	sc	Bridge cost study
Pavement costs	pc	Mass. Dept. of Public Works
Drainage costs	dc	Drainage analysis system
Interchange costs	ic	DTM design system or volumetric quantities program
Relocation costs	rc	Volumetric quantities program
Land costs	lc	Zone cost evaluation program
Percentage vehicles of class n	k	Mass. Dept. of Public Works
Fuel cost	fc	Vehicle simulation & operat. cost program
Tire cost	trc	AASHO "Red Book" (16)
Oil cost	oc	AASHO "Red Book" (16)
Vehicle maint. cost	mtc	AASHO "Red Book" (16)
Depreciation cost	dpc	AASHO "Red Book" (16)
Time to travel alignment	t	Vehicle simulation & operat. cost program
Unit time costs	tc	Engineer's discretion
Time unreliability costs	tur	Engineer's discretion
ADT volume	vol	Mass. Dept. of Public Works traffic data
Annual increase in traffic	av	Mass. Dept. of Public Works traffic data
Interest rate	i	Engineer's discretion
Service life	n	Engineer's discretion
Length of alignment	mi	DTM Location and Design Systems
Maintenance cost	mc	Maintenance cost program

allocated for the actual engineering efforts, thus making it imperative that this time be used efficiently. The Critical Path Method of planning was employed to allocate time and manpower. It proved to be an invaluable aid in the scheduling of work and was one of the prime factors in the completion of the study on time.

The actual link-node network used is shown in Figure 2. Although possibly somewhat meaningless to those unfamiliar with the Critical Path Method, it was perhaps the most important single document used in this approach. It serves to illustrate that there was an interdependent and logical flow of jobs from start (node 1) to finish (node 58). There is a total of 83 links, or jobs, and 52 nodes, or events.

A simplified event network indicates (Fig. 3) the basic relations of the more complete diagram (Fig. 2). Examination of this simplified network shows the interrelation-

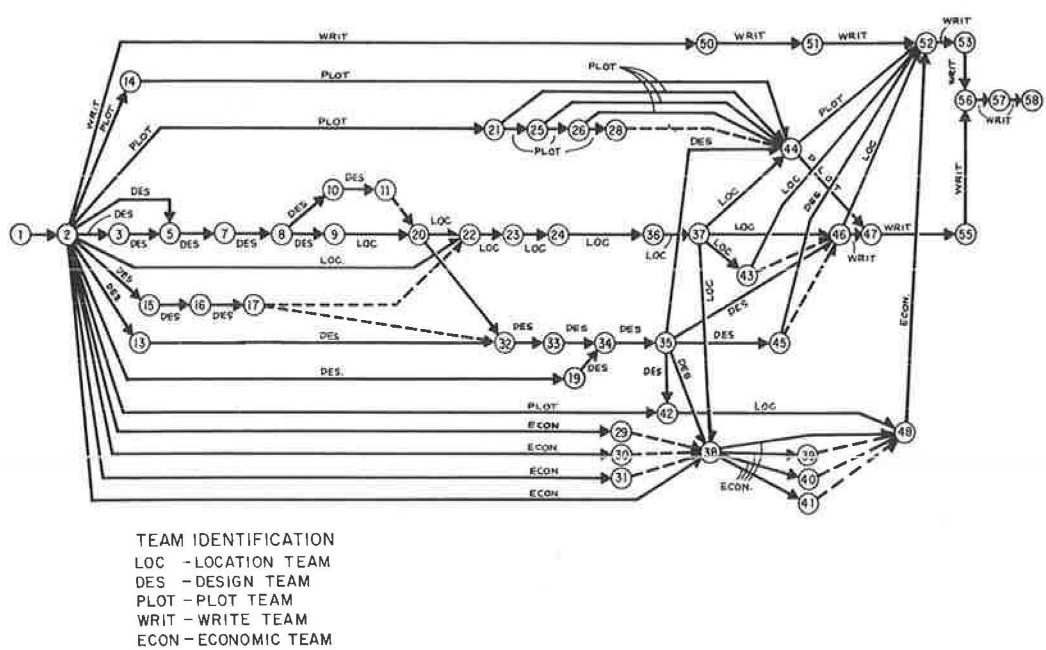


Figure 2. Location study arrow diagram.

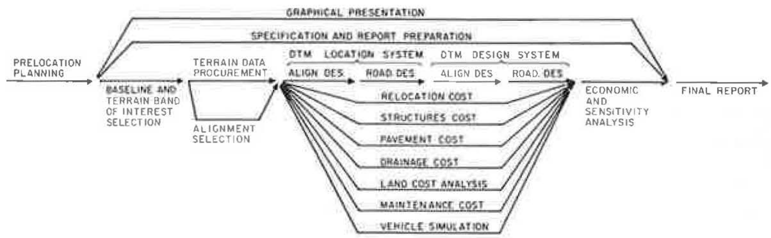


Figure 3. Simplified location study event network.

ship between the different mathematical models and serves as a graphical definition of the structure of the problem. A few of the more interesting of these arrows or events will be discussed.

EVALUATION OF PHYSICAL CONSEQUENCES

The Digital Terrain Model

A convenient representation of the earth's surface is a requirement for many civil engineering problems. In the past, this has been done by such devices as the topographic map, the physical model, and more recently the three-dimensional stereomodel. However, these are all essentially analog forms of terrain data, designed for human interpretation and utilization in mental and manual processes. They are not, at present, in a form that can be directly input to an electronic digital computer. Until this time comes, it will be necessary to put the terrain information into a form which the machine understands. At present, this must be some form of digital representation.

A second requirement is introduced if the full benefits of electronic computation are to be realized in the use of computer methods for highway location studies. The digitized terrain data should be in a form which permits the efficient consideration of a large number of possible solutions to the problem. These two requirements prompted the initial formulation of the Digital Terrain Model concept (8).

The Digital Terrain Model (DTM) is simply a sampling of the continuous surface of the ground by a number of selected points with known x, y, z coordinates in an arbitrary coordinate system. Terrain data are defined relative to a baseline (x-axis) and are taken along cross-section or scan lines (y-axis) normal to this baseline (Fig. 4). The reason for relating terrain data to a fixed baseline rather than to an alignment centerline is that, for any new trial alignment, it is relatively easy to re-establish the relationship of the new trial centerline to the baseline. This satisfies the second re-

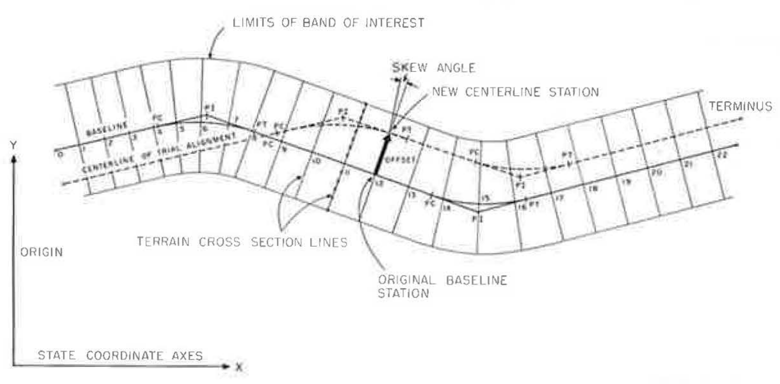
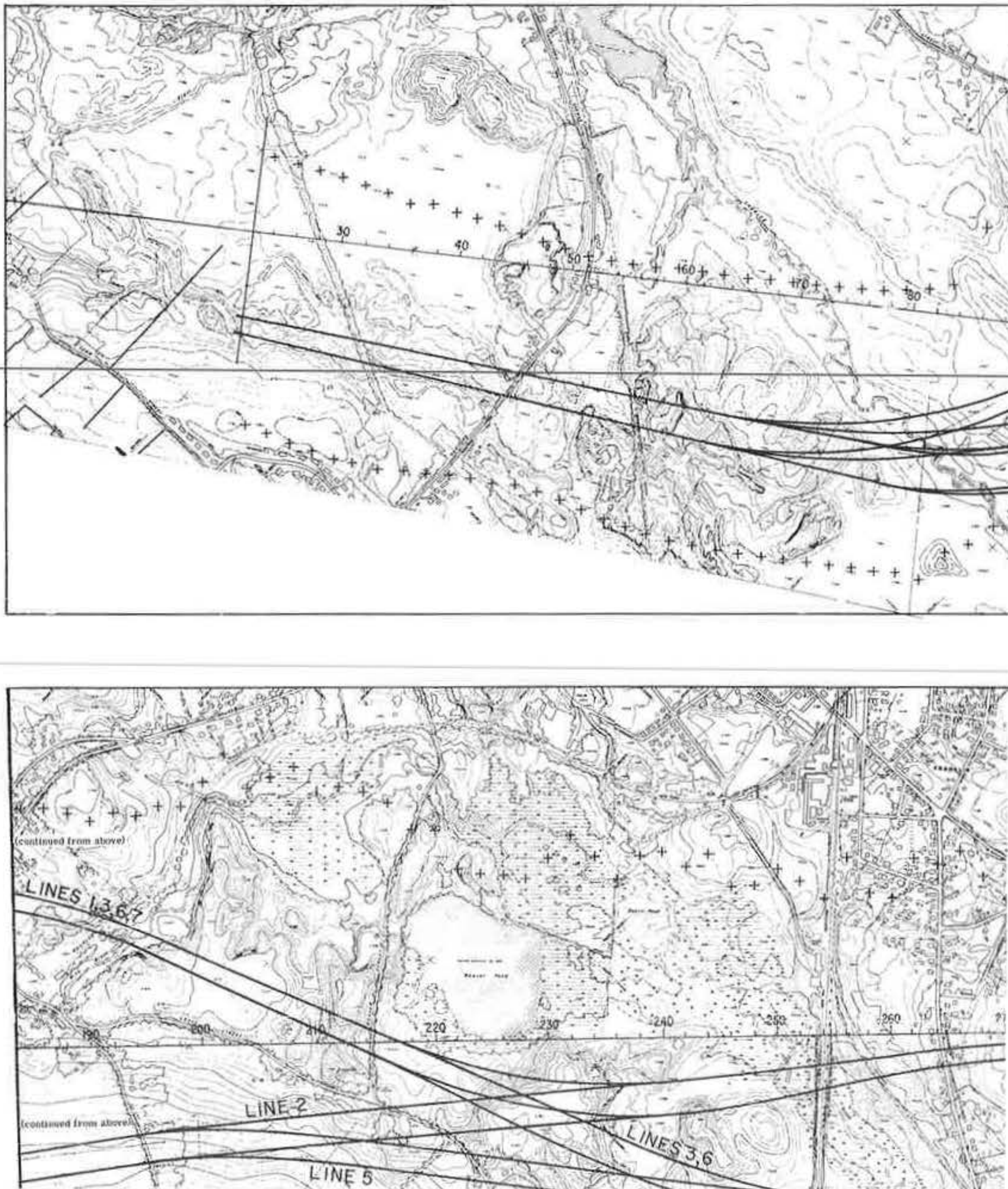


Figure 4. System nomenclature.


30
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(continued from above)
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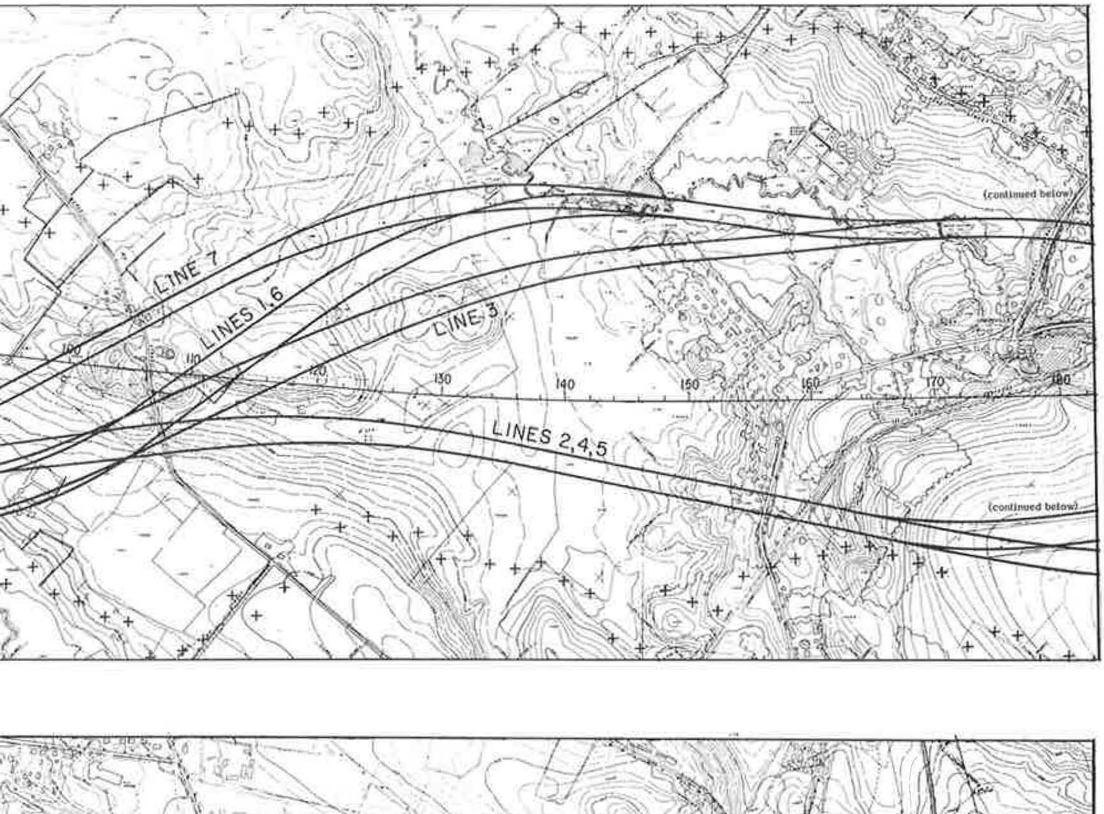
LINE 2
LINES 3,6
LINE 5
LINE 4

Figu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(continued below)
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Datum Mean Sea Level
1000 Foot Grid Based on
Massachusetts Rectangular Grid System

udy site.

quirement for a terrain data representation; namely, a model that can be used repeatedly for the rapid evaluation of many different trial lines without having to retake data.

Before the terrain data are taken, a band of interest must be selected by the engineer. In general, the width of this band varies with the phase that the location search-selection process is in and the amount of latitude that the location affords. In this particular problem, it was chosen so as to include all seven alternative alignments. This band of interest was then digitized for use by the computer.

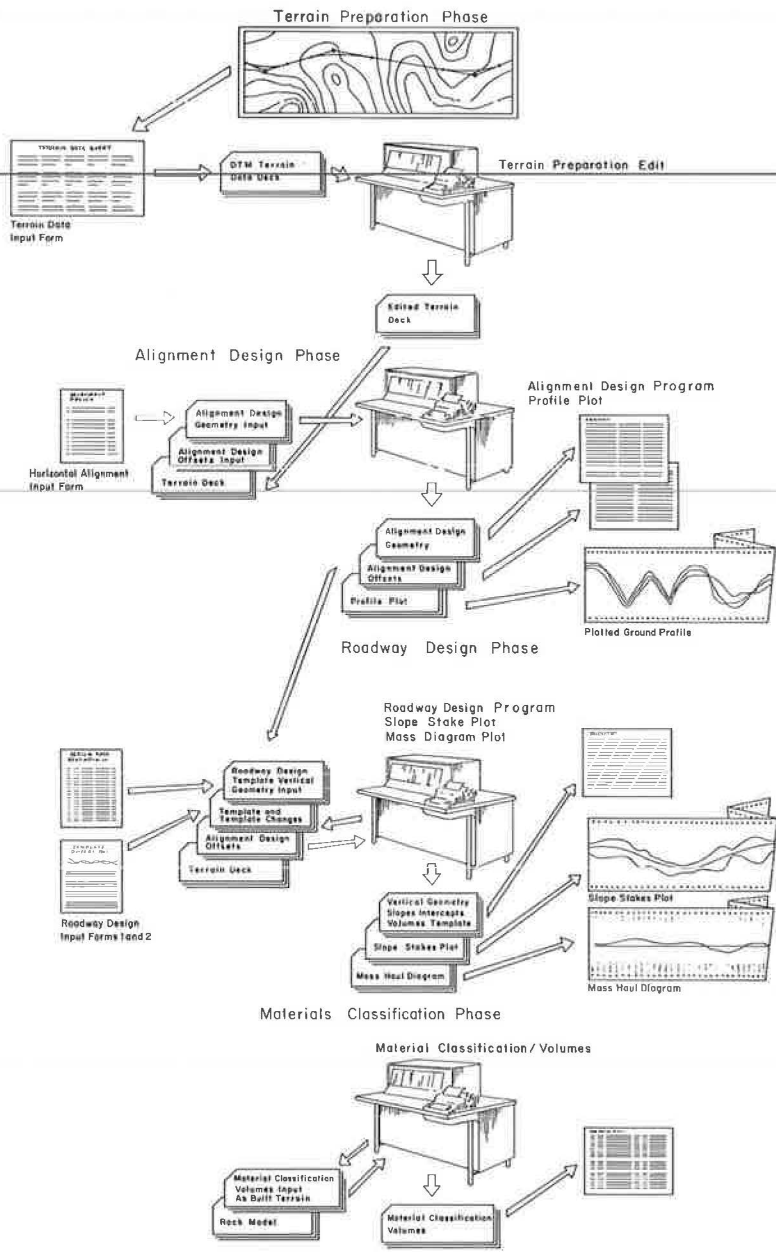

Figure 6. System flow chart.

The first step in this process is the definition of one or more baselines within the band of interest. These serve as the x-axis of the data coordinate system and can be composed of either straight-line segments or straight-line segments connected by curves, depending on the shape of the band of interest. Next, the surface of the ground is represented by a series of points. Sample points are taken from left to right across each cross-section and are referenced by giving the baseline station number (x-coordinate) of the cross-section line, their offset distance from the baseline (y-coordinate), and their elevation (z-coordinate). The spacing of the scan lines and the sample density of terrain points along a scan line depend on the accuracy required, the maps available, and the nature of the terrain. The selected baseline along with the limits of the recorded terrain and the seven alternatives investigated are shown in Figure 5.

Terrain data for the DTM can be taken directly from field notes, from topographic maps either by hand or through the use of special instrumentation, or directly from the stereomodel using automatic take-off equipment. Terrain data are taken only once and can be used for the evaluation of many lines.

Two separate systems of computer programs based on the DTM were used in this study. These are the DTM Location System (9) and the DTM Design System (Fig. 6) (10, 11). The programs that compose each of the systems are integrated so that they supplement each other while paralleling the design procedure followed by the engineer. Output from each system includes horizontal and vertical geometry, ground profiles, a description of the roadway template selected by the computer, the location of the points (slope stake limits) where the roadway side slopes intercept the terrain, earthwork volumes, and slope stake and mass haul plots (Fig. 7). In addition, the Design System has the ability to output "as-built" terrain cross-sections.

Although the two program systems are similar in structure and in input-output characteristics, there are some significant differences. The Design System uses a

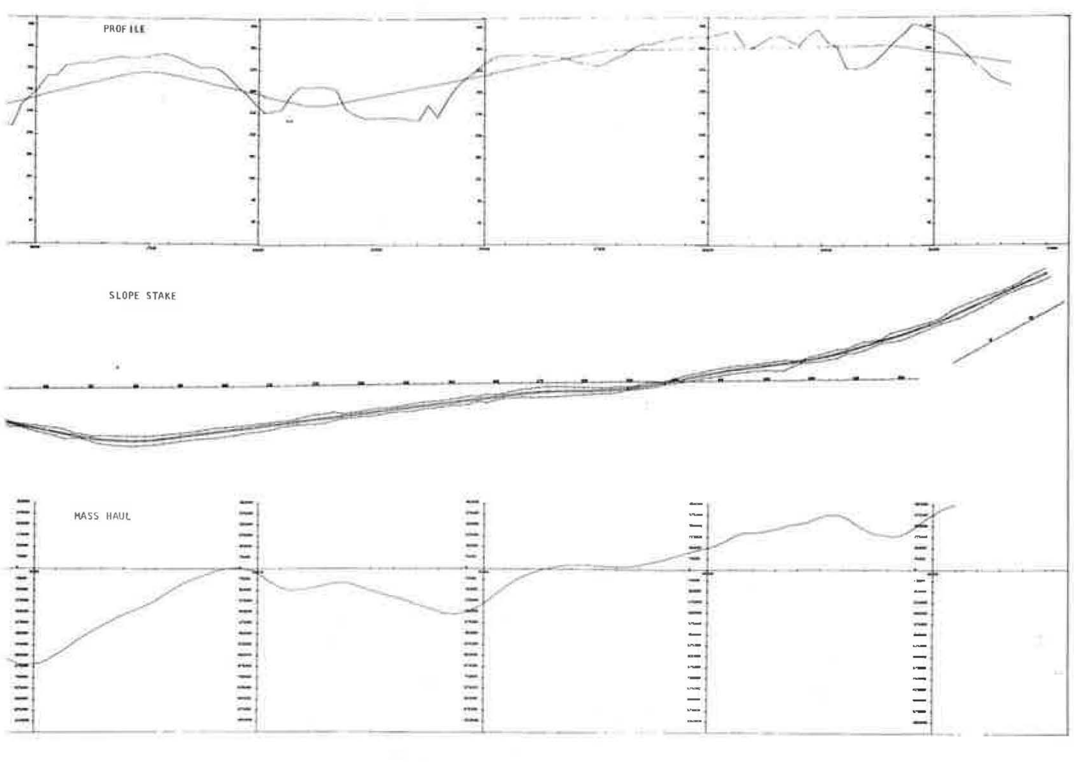

Figure 7. Profile, slope stake, and mass haul plots for line 2, southbound, produced by an on-line plotter.

twenty-one point roadway template and the actual terrain cross-section defined by the DTM, while the Location System employs a seven-point template and a five-point approximate terrain cross-section. The reason for these differences, and indeed the most basic, is the original purpose or intent of each of the two systems. The DTM Location System is intended for use in the early phases of a location study, where the emphasis should be on the searching out and preliminary evaluation of alternatives. The DTM Design System is intended for use in later phases of the study, where a more exact analysis is required and where the emphasis should be on studying the effects of small changes in the various alternatives. It is here that the added sophistication and smoothness of the Design System is required.

Final Alternative Selection

Even with the most modern of computers and the most advanced programming systems available today, to do a complete economic analysis of each of the seven alternatives would be time consuming and, probably, unnecessary. In any study, preliminary investigation would likely show that some alternatives are far better than others. By eliminating some of these alternatives early in the engineering process, more effort could go into the analysis of remaining alternatives and even into the search for additional alternatives. The DTM Location System is ideally suited to the process of preliminary location. Using this system, each of the seven lines was initially evaluated as to its effect on such items as balance of earthwork quantities, right-of-way requirements, drainage requirements, clearing and grubbing areas, and vehicle operating costs. The purpose of using the DTM Location System was not to reduce the number of alternatives from seven to exactly two or exactly three. Rather, it was to eliminate those alternatives that were obviously not the best, while at the same time searching for additional lines that might have been originally overlooked.

Examination of Figure 5 shows that each of the seven trial lines starts at one common point and ends at another. In between these two points, they branch off and diverge, sometimes coinciding with another line, sometimes paralleling another line. It can be imagined that these seven alternatives compose a network (Fig. 8) with each P.I. being looked upon as a node. Each of the seven major alternatives can then be thought of as a composition of a number of different links in this network.

This is the framework in which the output from the DTM Location System and the other preliminary investigations were analyzed. The actual analysis consisted of three parts. First, if two or more alternatives had a common link, it was determined which one of them was the best over just this one link. This was done for each link within the network. Second, by means of a simple least path algorithm, the best path through the network was determined. Third, the network was searched for other combinations of links which would form an alignment sufficiently close to the best path to merit additional investigation.

By means of this analysis, it was decided that alternatives 1, 2, and 5 were considerably better than the other four. The engineering location study of this portion of I-495 then continued with these three alignments as the major alternatives to be evaluated.

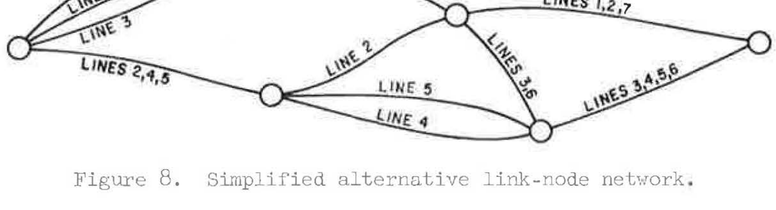

Figure 8. Simplified alternative link-node network.

Channel Relocation Problem

Close examination of the alignment of alternative one in Figure 5 shows that, for approximately 1,500 ft between baseline stations 135 + 00 and 150 + 00, the two barrels are separated by Mine Brook. In addition, the northbound lanes are shown passing over a small pond. If this alternative is chosen, portions of the brook will have to be relocated and parts of the pond will have to be filled in. The Volumetric Quantities program was employed to calculate the earthwork volumes associated with these hydraulic changes (12).

The purpose of the program is twofold: (a) to aid the engineer by removing the burden of hand calculation; and (b) to be versatile enough to compute any volumes where average end area computations are acceptable. For example, it can be used to compute borrow pit, stockpile, roadwork, dredging, foundation, ditchwork, or any of the other types of volume computations which typically occur on engineering projects.

The program is useful because of its ability to handle problems where slope intercepts are known as well as those problems where they are not known, and to do this with no extra work required on the part of the engineer. Further, the program treats every cross-section as a separate entity, thus eliminating the need for elaborate grid systems referenced to a single baseline (though such can just as easily be used if available or desirable).

Because of the way in which Mine Brook encroaches upon the embankments of both barrels of the new road, it was decided to relocate the bed by means of a permanent channel north of both barrels and roughly following the highway alignment. A terrain cross-section in the area where the brook interferes with alternative one is shown in Figure 9. Computing the amount of earthwork to be moved in this relocation is a problem ideally suited for this program. The template was simply one link 20 feet wide representing the width of the bottom of the channel. The desired slopes of the rip-rap embankments were given as input to the program, and the intersection of these slopes with the existing ground was calculated. Output at each section consisted of the location of these intersection points, the area of cut and fill, and the volume of earth to be removed.

Structures

A very important variable in the costing out of the various alignment alternatives of a study is the initial cost of structures or bridges. This can prove to be both difficult and time consuming. Most of the computer-oriented work that has been done in this area is more appropriate to design than to location. The engineer needs a technique which will enable him to quickly and accurately determine structures cost. Within the United States, if the location engineer has desired anything more reliable than a simple per-square-foot estimate, he has had to depend primarily on the bridge section. This usually entails a preliminary design for each structure. Such a technique is not only time consuming, but lacks the flexibility and speed required for the consideration of many alternatives.

A recently completed study had as its goal the development of a method which meets these flexibility and speed requirements (13). The costs and configurations of a large number of bridges were statistically analyzed and a number of formulas developed. The results of this study were then used to estimate the structures cost for each alternative under consideration.

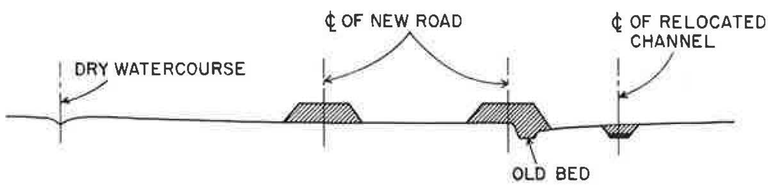

Figure 9. Typical cross-section showing centerline of relocated channel.

Coefficients for more than 20 separate formulas were estimated from data for 126 bridges by the method of least squares.[2] The terms of each of these equations involved simple expressions of length, L, width, W, clearance, H, number of spans, N, and cosine of the skew angle cos α. For example, an expression of WL represents the area of a bridge, while $WL^{4/3}$ or $WL^{3/2}$ is representative of the volume. The following equations are typical of those investigated:

$$C = A_0 + A_1\ WL^{4/3} + A_2\ WL + A_3 \frac{WH}{\cos\alpha} (N + 1) + A_4 \frac{WH}{\cos\alpha} (N + 1) +$$

$$A_5\ L^{4/3} + A_6\ L + A_7\ H + A_8\sqrt{H} \tag{14}$$

$$C = A_0 + A_1\ WL + A_2 \frac{WH}{\cos\alpha} (n + 1) \tag{15}$$

$$C = A_1\ WL + A_2 \frac{WH}{\cos\alpha} (N + 1) \tag{16}$$

where

C = cost of structure in dollars, and
A_i = constants.

Histograms showing the goodness of fit of Eqs. 15 and 16 are shown in Figure 10. Although the standard deviation of Eq. 16 is slightly higher than that of Eq. 15 (18.57 compared to 18.15), this equation was selected for use in this study because of its simpler form.

The average per-square-foot cost of these same bridges was determined to be \$20.90. Using this unit price as an estimate of predicted cost, the results are significantly poorer (a standard deviation of 31.35%) than with either of the other equations (Fig. 10).

The use of this particular equation or any statistical analysis is not expected to be useful, nor is it intended, for the estimate of a single bridge at the design stage. This type of approach is useful primarily during the early stages of a highway location project where the cost of bridges is only one variable in a total economic analysis. It should be noted that the predicted total cost of all the bridges will have a higher probability of being estimated correctly than the cost of a single bridge. In statistical terms, the standard deviation, σ_n, of the total cost of several bridges, N, will be equal to the standard deviation, σ, of the cost of a single bridge divided by the square root of the number of bridges, i. e., $\sigma_n = \frac{\sigma}{\sqrt{N}}$.

Drainage Analysis

Although the cost of providing adequate drainage facilities is not typically a major item in the initial capital cost of a highway project, the engineering effort to design properly these facilities is frequently quite large. The investment in engineering and

[2] The 126 bridges were selected from an original sample of 132 and consisted of 72 single- and 54 multi-span structures built by the Maine State Highway Commission between 1959 and 1961. They ranged from 10 to 548 ft in length, 15 to 84 ft in width, 8 to 44 ft in clearance, and \$4,965 to \$324,634 in cost.

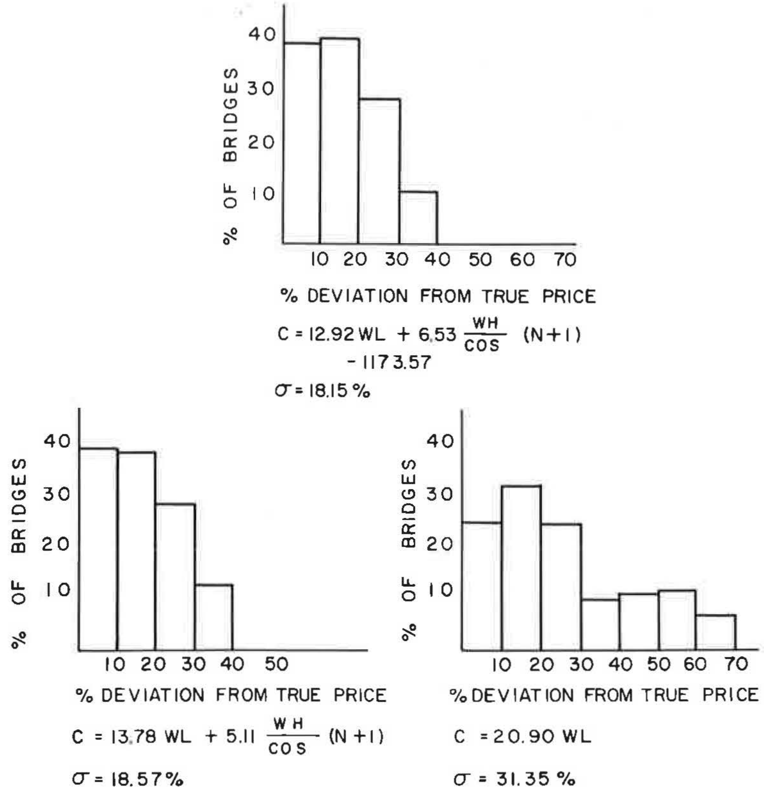

Figure 10. Bridge cost histograms.

the cost of the facilities may be thought of as insurance against the large losses which may occur should the drainage prove to be inadequate. In some cases, both the absolute magnitude of the drainage cost and the cost differential between the drainage requirements of alternative alignments may be quite small. If this is the case, estimation of these costs may be deleted as irrelevant to the decision process. In most situations, however, some estimate of drainage cost is needed for comparing alternatives at different levels of service.

The design of drainage is basically an empirical process which is not easily adaptable to electronic computation. Drainage areas, typically obtained by planimeter, are used to compute run-off quantities for the sizing of culverts and waterway openings. Where major structures on large, non-standard culverts are involved, detailed design may be necessary before costs can be completed. In the majority of cases, the bulk of the drainage design consists of the detailing of drains, inlets, ditches, collector systems, and culverts over the entire job and the summation of these quantities for use in the cost estimate. In this essentially bookkeeping operation, a computer can be quite useful.

The DTM Location and Design Systems develop a large amount of geometric information concerning the relationship of the roadway to the terrain. This information is not, however, in a form readily usable by the engineer in the drainage design process. A program has been developed and was used in this study to organize and extend the basic output of the DTM Systems into a more useful form for drainage analysis.

The output of this program is basically a station-by-station summary of the direction in which run-off water will flow at five points on the completed roadway cross-section: the two slope intercept points, the two hinge points, and the centerline. For presentation, this information is plotted in both vertical and horizontal form by means of an on-line plotter (Fig. 11). The direction of water flow is indicated by arrows. The program also produces string length accumulations of ditch for a given flow direction. These figures, along with the gradient of the flow will enable the design engineer to size pipes quickly and to identify points where inlets, cross ditches, or downspouts should be located or where ditches should be paved to prevent erosion. The program will also identify slope change points, locate culverts and compute their lengths, indicate an interceptor ditch where water flows toward the road, and indicate those areas where guardrails may be required.

The purpose of the program is not to machine design the drainage, but to accumulate the information necessary for the designer to do the job quickly and accurately. Hand methods of design utilizing cross-sections and hand computation tended to familiarize the engineer with the job to a degree which is not possible using more rapid computer-oriented methods. The role of data organization and presentation is becoming quite important to decision-making processes.

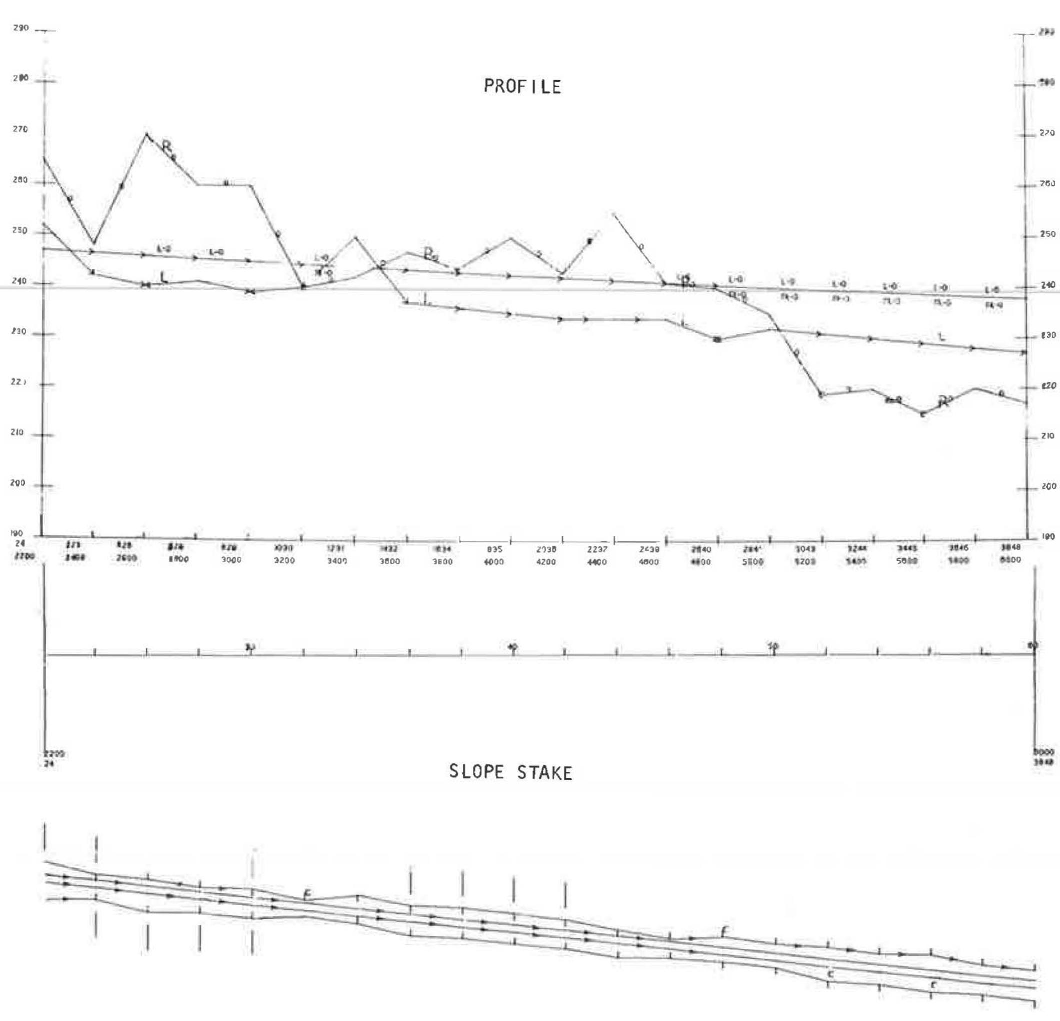

Figure 11. Profile and slope stake drainage plots for a portion of line 2, southbound, produced by an on-line plotter.

User Operating and Time Costs

In the typical route location problem, the costs associated with road users far outweigh the initial capital expenditures. Road user costs are characterized by small unit costs multiplied by a large number of trips. The evaluation of these costs involves both an extremely sensitive measure of these unit costs and a realistic idea of the number of trips which will be affected by the building of a facility. In the usual case, this means that the engineer must accurately predict the amount of future travel, a very difficult task, especially if the primary purpose of the highway facility is to open up untapped resources. In the problem under discussion, it was assumed that the amount of future travel on each of the alternatives would be the same. This is not unrealistic as the level of service is essentially the same on all choices.

The determination of the small unit costs consists of the calculation of direct operating costs and of user time costs. Direct operating costs can be determined by the Vehicle Simulation and Operating Cost System (14, 15), the AASHO "Red Book" (16), or a number of other "handbook" procedures, while an accurate estimate of the travel time, praticularly that of trucks, can best be made with the vehicle simulation programs. It was therefore decided to use the Vehicle Simulation and Operating Cost System to determine fuel costs and user time costs for each alternative. The latest AASHO estimates of tire, oil, maintenance, and depreciation costs were then added to the fuel cost to determine the total direct operating cost.

The purpose of the Vehicle Simulation and Operating Cost System is to aid in the determination of unit costs by calculating the costs of fuel and of user time for each alternative. This is accomplished by modeling or simulating the operation of a vehicle over a specified highway alignment and determining the associated costs involved in this movement. Vehicle operating costs are a direct function of vehicle road speeds, engine RPM, vehicle tractive effort, and percent of full engine load. These four items are, in turn, directly related to certain highway design characteristics selected by the engineer. These characteristics include the vertical alignment or profile, the unbalanced side force caused by curves (superelevation), the pavement type, and the operational restrictions placed on speed. The programs within the Vehicle Simulation and Operating Cost System take these design characteristics and a description of the vehicle and calculate the consequences of these characteristics on engine performance. These consequences are then converted into associated costs.

Input to the system includes vehicle data, control data (wind speed, pavement type, fuel cost, time cost, traffic volumes, etc.), desired speed profile data, vertical and horizontal alignment data, and a fuel performance table. Output includes the time and speed at which the vehicle passes each station on the roadway along with certain information pertaining to both the cost and the amount of fuel consumption at each station. In addition, a summary table is output at the end of each run which includes a summary of all pertinent operating and cost information.

Certain decisions regarding this input data had to be made before the actual production runs could begin. The more important of these decisions are summarized and discussed.

It was decided that three types of vehicles would be run over each of the three final alternatives, once in the northbound direction and once in the southbound. A 1960 Plymouth station wagon with automatic transmission was selected as being representative of passenger vehicles, while a 1960 Ford 2-ton stake body truck with no load and 1960 International tractor-trailer with full load were selected to represent truck traffic. Past data showed that the traffic volume split was approximately 95 percent cars, $2\frac{1}{2}$ percent small trucks, and $2\frac{1}{2}$ percent large or heavy trucks.

The estimation and prediction of future traffic volumes on any highway segment is both a very large and a very important problem. Unfortunately, much money has been spent in the construction of elaborate highway systems only to find either that they were totally inadequate and outdated within a few years or that there was little or no demand for such a facility. Work is presently going on within the Civil Engineering Systems Laboratory at M.I.T. and in other organizations as well to solve this problem. However, the prediction of demand for the Franklin portion of I-495 was not, as such,

TABLE 2

SUMMARY OF USER TIME AND OPERATING COSTS TO TRAVEL ALIGNMENT[a]

Alternative		Car					Small Truck					Large Truck				
Line	Direction	Time (hr)	Cost ($)	Fuel (gal)	Cost ($)	Total Cost per Veh ($)	Time (hr)	Cost ($)	Fuel (gal)	Cost ($)	Total Cost per Veh ($)	Time (hr)	Cost ($)	Fuel (gal)	Cost ($)	Total Cost per Veh ($)
1	NB	0.127	0.197	0.295	0.089	0.538	0.127	0.508	0.753	0.226	0.987	0.130	0.519	1.475	0.443	1.215
	SB	0.129	0.200	0.333	0.100	0.556	0.129	0.512	0.817	0.245	1.018	0.146	0.586	1.724	0.517	1.359
2	NB	0.125	0.193	0.288	0.086	0.527	0.125	0.499	0.741	0.222	0.968	0.128	0.510	1.378	0.413	1.170
	SB	0.127	0.196	0.329	0.099	0.546	0.127	0.505	0.802	0.241	0.997	0.142	0.567	1.691	0.507	1.325
5	NB	0.126	0.195	0.293	0.088	0.533	0.126	0.503	0.749	0.225	0.978	0.128	0.512	1.466	0.440	1.202
	SB	0.128	0.198	0.329	0.099	0.549	0.128	0.510	0.806	0.242	1.005	0.144	0.574	1.702	0.511	1.338

[a]Total cost per vehicle includes oil at $0.0037/mi, tires at $0.0054/mi, maintenance and repair at $0.012/mi, depreciation at $0.015/mi, fuel at $0.30/gal, time for car at $1.55/hr and for small and large trucks at $4.00/hr.

part of the problem under immediate consideration, and data provided by the Massachusetts Department of Public Works were relied on. Average daily traffic volumes of 7,330 for 1958 and 26,035 for 1975 were selected. It turns out, as will be shown later, that the choice among the three final alternatives is independent of traffic demand.

Fuel cost for all three vehicles was selected as $0.30 per gallon (taxes should not be included in the cost of fuel). The selection of a unit value of time was a more difficult task since this is an extremely controversial matter. While it is generally agreed that time is of value to a commercial vehicle and that $4 per hour is not too bad an estimate of this value, there is very little agreement on time costs for the non-commercial user. Estimates vary from $0 (no value) to as high as that of commercial vehicles. In an attempt to solve this problem, it has been postulated that the values of time be defined as a probability distribution. Certainly this explanation would account for the range of values encountered. If this postulate is accepted, the cost of user time is then the product of the mean value of this distribution and the time to make the trip. Lacking adequate data to construct such a distribution, the mean value of time for passenger vehicles was arbitrarily selected as $1.55 per hour and that for commercial vehicles as $4 per hour.

Past work has shown that the speed profile which results in average costs is only slightly different from the average speed profile (17). Accordingly a profile of 55 mph with no variations or stops was selected for this problem. This ignores any slowdowns or other problems due to congestion, but the projected volume levels would indicate that these should not be serious.

The vertical geometry data for the Vehicle Simulation and Operating Cost System were obtained from the DTM Design System output.

The system was used with the foregoing input data to obtain estimates of fuel and time costs for each of the vehicle classes over each alignment. The results of all the output along with oil, tire, maintenance and repair, and depreciation costs are summarized in Table 2.

One thing is immediately obvious from an examination of these data. For both time and fuel costs and for all three vehicle types, line 2 is better than line 5 which is, in turn, better than line 1. However, this is not the only information of value obtained from the vehicle simulation runs. Probably of greater importance to the quality of engineering being done is the information obtained from an examination of the speed and fuel profiles for each vehicle type over each alternative. These two profiles, along with the vertical profile, for the southbound barrel of line 2 are shown in Figure 12.

The fuel profiles indicate that the rate of fuel consumption for all three vehicles increases markedly on the long uphill grades. In fact, it would appear that the heavy truck has a great deal of trouble. The speed profiles confirm this point. While the car and the small truck are able to maintain a speed of 55 mph, the speed of the heavy truck varies from the 55-mph limit to a low of $36\frac{1}{2}$ mph. This would have two effects on the operation of the facility. The first is the obvious point of high truck operating costs. The second effect would be on congestion. As the large trucks slow down and the traffic volumes increase, all vehicle classes will be slowed down appreciably. This overall slowdown tends to slow the large trucks even more. These problems could be solved by revisions in the vertical alignment or by provision for a truck climbing lane. Although the majority of the grades are in the range of 1-2 percent, their lengths may be too great. It is possible that shorter, higher grades would prove more satisfactory.

The point to be made is that the Vehicle Simulation and Operating Cost System does more than merely predict fuel and time costs for the engineer. If used properly, it can serve as a very critical judge of the merit and worth of the various vertical alignment possiblities.

ECONOMIC SUMMARY

Cost models for some of the variables comprising the basic annual cost equation have been discussed. It remains to summarize the costs for each alternative, com-

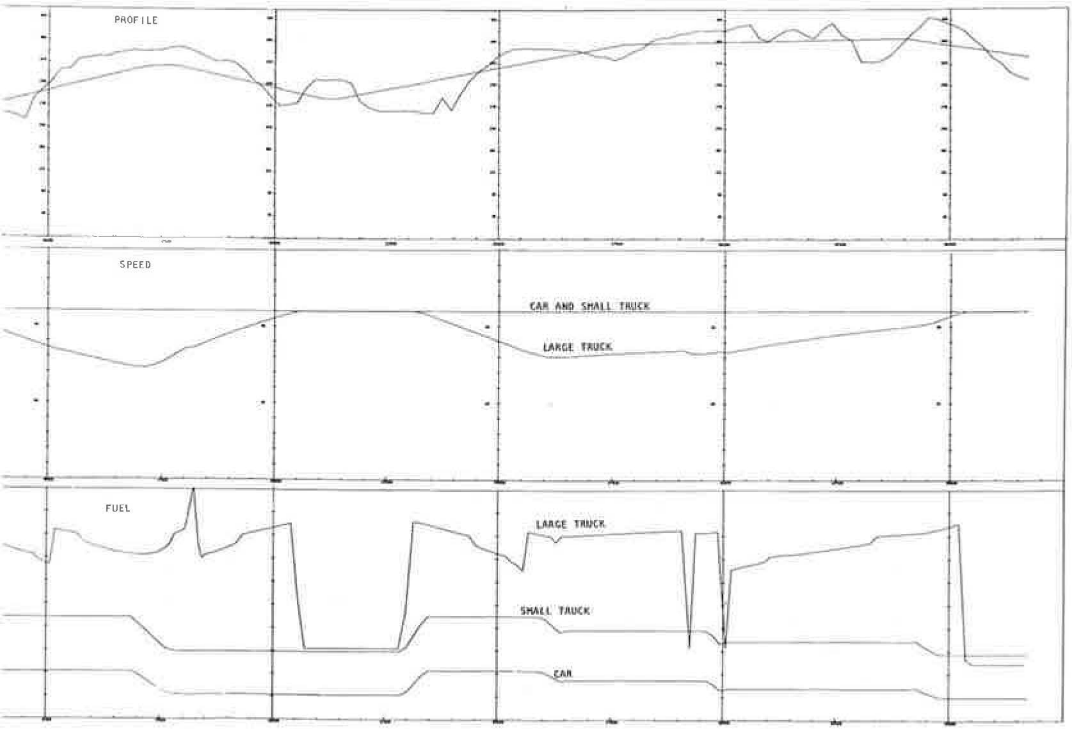

Figure 12. Profile, speed, and fuel consumption plots for line 2, southbound, produced by an on-line plotter.

bine them into equivalent annual costs by means of the cost equation, examine the effect of variability of input through a sensitivity analysis, and finally present the results of the location study in a graphical manner for analysis and decision. User costs have already been summarized in Table 2. A summary of the capital and maintenance costs is given in Table 3.

Several of the variables given in these two tables, notably user time costs, annual traffic growth, interest rate, and service life, are probabilistic in nature. The values given for these items are their expected values. If these expected values are used in the annual cost computations, the following results are obtained:

Line 2	Line 5	Line 1
$3,842,900	$3,885,354	$3,923,452

Although these three estimates are very close, the proper choice, from a probabilistic or expected value point of view, would be line 2. It should be noted, however, that the probable error of each of these estimates is almost certainly larger than any of the differences between them.

It is interesting to look at the percentage breakdown of annual cost in terms of the three major variable classifications (Fig. 13). Road user costs contribute roughly 90 percent in all three cases, of which roughly $\frac{2}{3}$ is time and $\frac{1}{3}$ operating cost. Initial capital costs account for 9 percent of the total, while in this problem highway maintenance costs contribute only 1 percent to the total annual cost.

It may be interesting to examine the cost summary of Tables 2 and 3 more closely. Although the costs vary from line to line, the following rough percentage breakdown of direct operating costs is found to exist:

TABLE 3

COST SUMMARY TABLE

Cost Components	Total		
	Alternative 2	Alternative 5	Alternative 1
Length of alignment (mi)	6.91	6.97	7.04
Existing traffic volume (veh/yr)	2,680,000	2,680,000	2,680,000
Annual increase in traffic (veh/yr/yr)	401,200	401,200	401,200
Interest rate (%)	6.0	6.0	6.0
Service life (yr)	20.0	20.0	20.0
Construction ($):			
Earthwork	1,696,628	1,813,114	1,807,041
Structures	801,257	867,301	840,138
Pavement	1,035,200	1,045,400	1,056,900
Drainage	58,820	64,060	87,400
Land	301,000	153,000	200,000
Total	3,892,900	3,942,900	3,991,500
Maintenance ($/mi)	5,960	5,960	5,960
Equivalent annual user costs ($/yr):			
Automobiles	3,125,524	3,151,740	3,186,694
Small trucks	150,627	152,007	153,693
Large trucks	191,254	194,703	197,309
Total	3,467,408	3,498,450	3,537,696
Total Annual Costs ($)	3,842,900	3,885,354	3,923,452

Fuel	30%
Depreciation	29%
Maintenance and Repair	23%
Tires	11%
Oil	7%
Total direct operating costs	100%

Construction costs break down approximately as follows:

Earthwork	43%
Pavement	27%
Structures	20%
Right-of-way	8%
Drainage	2%
Total construction costs	100%

SENSITIVITY ANALYSIS

Methods for estimating costs of items such as earthwork, structures, drainage, and direct operating costs of vehicles are definable and have been discussed, but these methods still produce only estimates. There is a definite distribution of values associated with each of these estimates. Values for such items as user time cost, predicted traffic volumes, interest rate, and service life are considerably more difficult to estimate and will have a correspondingly wider range of possible values. A sensitivity

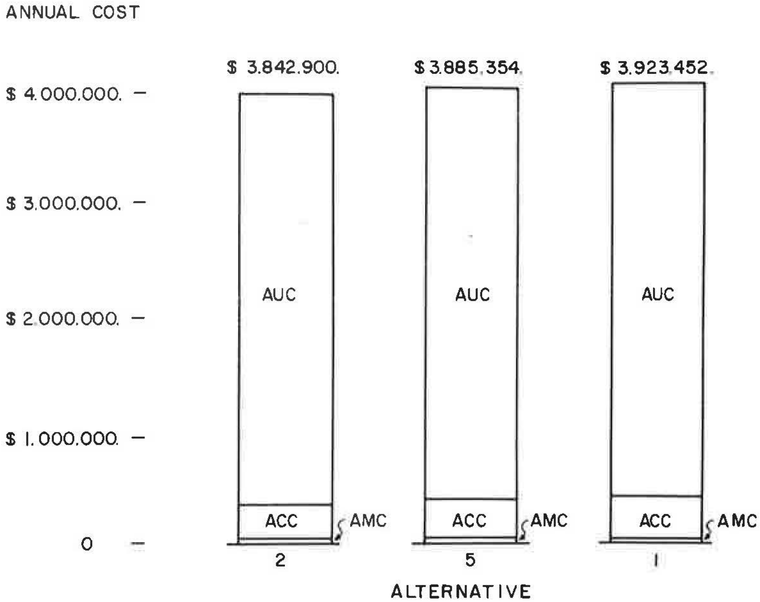

Figure 13. Breakdown of total annual cost into user, construction, and maintenance cost components.

analysis is a study of the relationships between changes in the value of the probabilistic input variables of the cost equation and the rank ordering of alternatives. By such means the engineer can determine how sensitive decisions are to intangibles, unexpected events, and to variations or error in input data.

For the problem under consideration, it turned out that such an analysis did not reveal much of interest. As can easily be verified from Tables 2 and 3, line 2 is better than the other two lines on all counts. For each of the three major variable classifications, initial capital cost, road user cost, and maintenance cost, line 2 is lower than either line 5 or line 1. No matter how service life, interest rate, traffic volume, or user time costs vary, the answer will be the same; line 2 will have the lowest annual cost.

However, suppose that three alternative alignments, A, B, and C, are to be compared. Suppose further that C has a low construction cost and high user costs, A has higher construction costs but a lower user cost and B has very high construction costs but very low user cost. If this case is typical, it might be interesting to investigate the sensitivity of traffic volumes, interest rate, and service life, as these are variables to which it is commonly difficult to assign specific costs. In this problem it would probably be found that under low traffic volumes, low interest rate, and short service life, alternative C was preferred to A which was preferred to B. However,

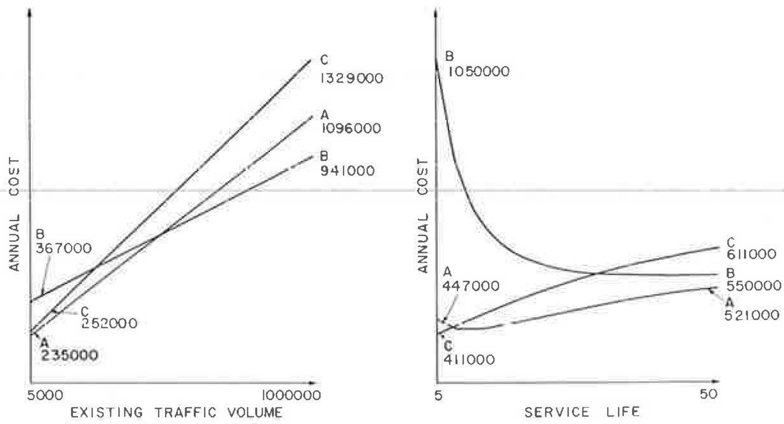

Figure 14. Example plots from a typical sensitivity analysis.

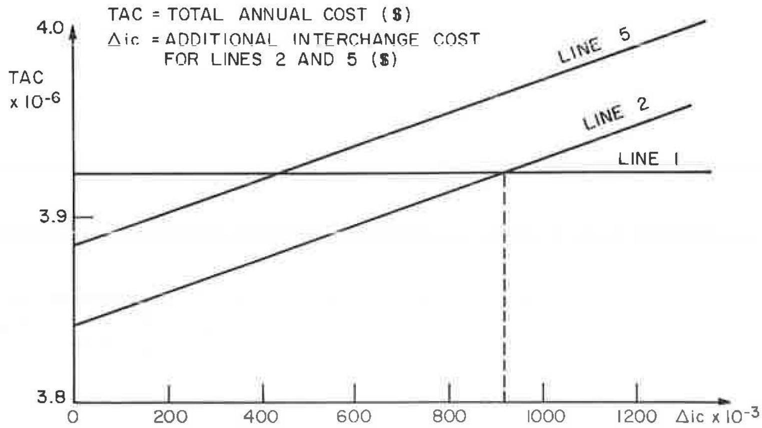

Figure 15. Variation of total annual cost as a function of interchange cost.

under a combination of high traffic volumes, low interest rate, and long service life, the rank ordering of the alternatives by annual cost might show B preferred to A preferred to C (Fig. 14). It is now up to the engineer to decide what value of each of the variables he is to use. He is not relieved of the responsibility for making decisions; he is merely allowed to make them in full light of the consequences.

The use of sensitivity analysis could improve the approach to the engineering of location. After a few rough cost estimates have been assembled, the engineer might investigate their sensitivity to determine which elements need to be defined further. He might, for example, find that earthwork was not very important. It might vary by ± 50 percent and still not affect the rank ordering of alternatives. He might also find that the equation was very sensitive to traffic volume figures. From the analysis, it could be determined that improvement was necessary in these traffic estimates before a decision between alternatives could be made.

Another use might be in the determination of the effect of location on unusual structures, particularly where it is difficult to arrive at estimated costs for these facilities during the location phase. By determining all the other costs for each of the alignments except those for the major structure, it is possible to determine what the difference in cost for these items would have to be in order to change the rank ordering of the alternatives. For the I-495 problem, this is the manner in which interchange costs were investigated.

In the initial economic analysis, it was implicitly assumed that the cost of interchanges would be the same on each of the three alternatives. If this were true, it is permissible to omit this item altogether since it contributes equally to all three alignments. However, this is not the case. It had been decided that an interchange would be located at the junction of I-495 and West Central Avenue. Examination of Figure 5 indicates that because of the New York, New Haven and Hartford Railroad, the cost of this interchange is likely to be higher for lines 2 and 5 than for line 1. By varying the initial construction costs of lines 2 and 5, it was determined that the additional cost of the interchange for these two choices could be as much as $920,000 more than that of line 1 before the original decision to build line 2 would change (Fig. 15). It was assumed that the additional cost for this structure on lines 2 and 5 would probably not be this great so that the decision to select line 2 is unaffected. The decision was thus made without the expenditure of any time or effort in the actual design of interchanges.

Figure 16. California Computer Product's incremental plotter attached to an IBM 1620 Data Processing System.

If least annual cost is to be used as the criterion for selection, line 2 will be the choice. Differences between the three final alternatives in terms of number of people and businesses disrupted or in social, political, and aesthetic impact upon the community were not felt to be sufficient enough to change the decision.

PRESENTATION OF RESULTS

For most highway location or design studies, the results are typically presented in the form of drawings. These drawings include the route plan, the centerline profiles of the roadway and the terrain, and frequently the terrain cross-sections and mass haul diagram. Several reasons can be stated for the desirability for such a graphical presentation. First, drawings permit relationships to be visually appreciated. The overall picture is more readily apparent in a plot than in the obscurity of large masses of numerical information. Second, drawings tend to point out errors that otherwise might not be detected. Last, a graphical representation helps to convey to an engineer certain design details. Without the benefit of a computer, an engineer is forced to do a complete design and evaluation analysis himself. In this process, a large amount of knowledge pertaining to the detailed relationships of the roadway and the terrain is gained, thereby permitting, on the basis of intuition alone, modifications which improve the alignment. The engineer who has made use of a computer, however, will not have

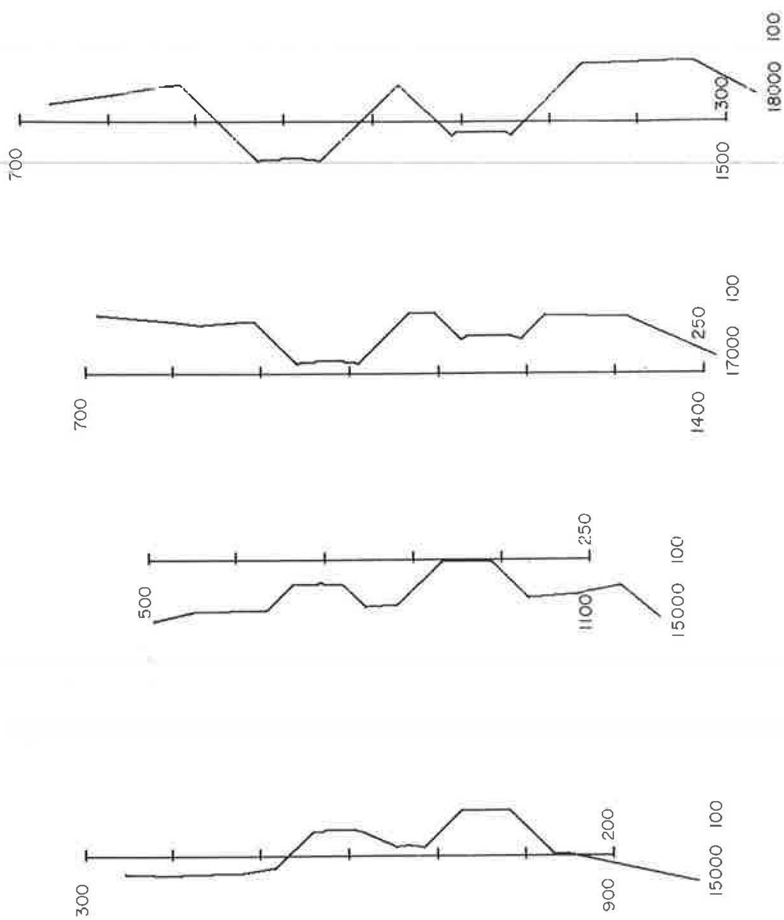

Figure 17. Examples of automatically prepared as-built cross-section plots.

the opportunity to gain such knowledge. He has merely specified certain general criteria, and the machine has handled many of the design details. Very often, the computer-aided engineer will be aware of general relationships, but he frequently does not gain the detailed knowledge which permits him to intuitively make alignment improvements. Here plots are of the utmost usefulness; they convey those details which permit the engineer to decide on modifications to improve the alignment layout. It is necessary, therefore, in a computer-aided analysis, to present results graphically not only for the final choice, but for each alternative under consideration. It is imperative, if high efficiency is to be achieved with today's high-speed data processing systems, that this plotting be done rapidly and automatically (18).

An automatic plotting facility has recently been installed in the Civil Engineering Systems Laboratory. This facility is a California Computer Products incremental plotter, connected on line to the laboratory's IBM 1620 Data Processing System (Fig. 16). Significant advancements in the visual conveyance of information to the engineer have resulted from the added flexibility and accuracy provided by this installation. Programs have been written to draw the limits of the band of interest (Fig. 5), the centerline profiles of the roadway and terrain (Fig. 7), the slope limits plot (Fig. 7), the terrain (either the original or "as-built") cross-sections (Fig. 17), the mass haul diagram (Fig. 7), and the sensitivity analysis results. If desired, individual plots can be combined into composites for use as preliminary design plans (Fig. 18). These sample plots emphasize the point that automatic on-line plotters are opening up entirely new areas of computer applications to the highway engineer.

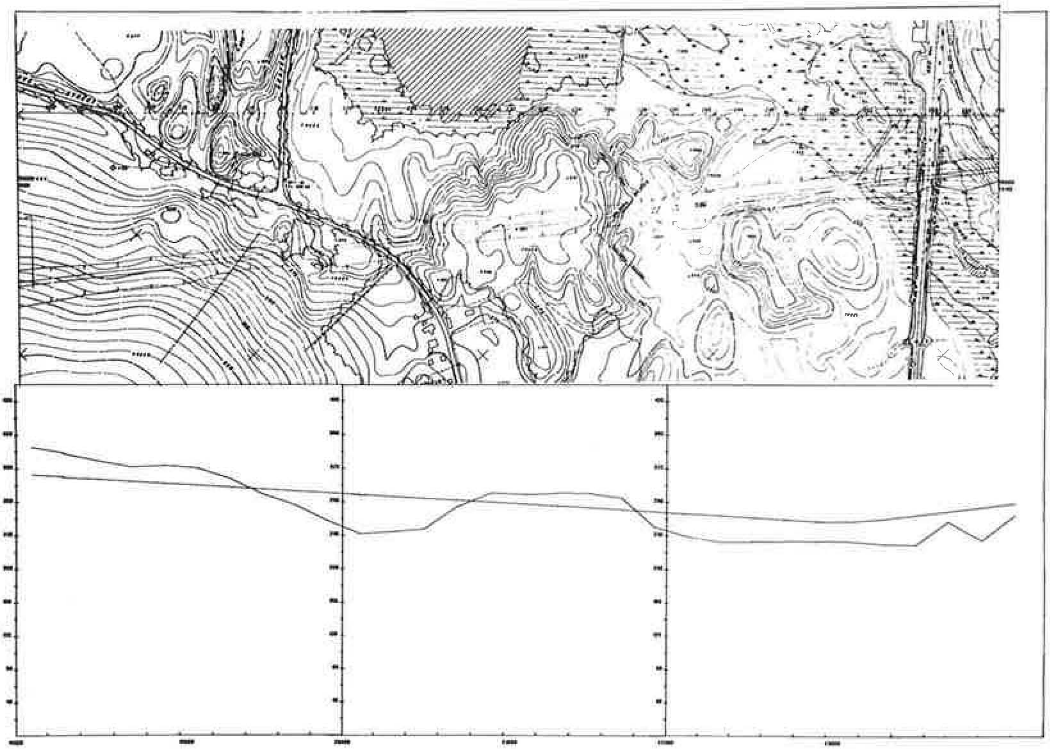

Figure 18. Typical sheet of a set of automatically prepared preliminary design plans.

CONCLUSIONS

This paper has described, in the context of an actual study, the application of several computer-based methods to highway location and design problems. Most of the specific mathematical models that were used to evaluate each of the cost-producing variables presently exist as individual programs or integrated systems of programs. However, with the advent of disk storage for small- and medium-scale computers, an integrated "route location evaluation system" becomes feasible. An engineer, in a single "pass" through the computer, would be able to describe completely his problem in highway terminology, analyze those phases in which he is currently interested, and obtain the resulting information in the form of listings and automatically prepared plots.

Although the problem under discussion is in a rural area, the underlying methodology is valid for both rural and urban problems. The same cost variables are present in both situations; however, their relative importance can be vastly different. For example, it was determined that the critical variables in this study were user time, fuel costs, and cost of earthwork. The cost of structures, although important, was less than half of that for earthwork. Social and political factors were relatively minor. If the problem under consideration had been in an urban area, the investigation of social impact, network systems effects and the role of structures and land cost would likely have been important. The prediction of travel demand would not only be critical to the study, but also it would have to be done separately for each alternative under investigation. Computer models used in the evaluation of the various cost variables for urban studies are typically quite different from those used in rural situations.

Also important is the hierarchical level at which the location decision is to be made. The discrimination in the models used to locate the roadway is necessarily greater than that required to locate the band of interest. The relative importance of the different variables involved may also change with level. On a macro level, travel demand is almost always important. Once the travel volumes have been established, the construction costs usually become more significant.

Finally, the analysis of a highway location, be it economic, social, political or aesthetic, involves the consideration of probabilisitic variables. If such an analysis is to be of value, it must attempt to deal realistically with these quantities. Digital computer programs and methods of analysis now exist which make such an analysis much more feasible than ever before. The use of these methods by engineering agencies will inevitably result in better engineering, better functioning facilities, and in the long run, increased responsibility on the part of the engineer as a decision maker for public policy.

REFERENCES

1. Manheim, M. L. The Hierarchical Structure of a Highway Location Problem: An Experiment in the Use of Statistical Decision Theory for Guiding an Engineering Process. Unpubl. Ph.D. Thesis, M.I.T., June 1964.
2. Grant, E. L., and Oglesby, C. H. Economy Studies for Highways. Highway Research Board Bull. 306, pp. 23-38, 1961.
3. Lang, A. S., and Wohl, M. Evaluation of Highway Impact. Highway Research Board Bull. 268, pp. 105-119, 1960.
4. Grant, E. L. Concepts and Applications of Engineering Economy. Highway Research Board Spec. Rept. 56, pp. 8-18, 1960.
5. Manheim, M. L. Data Accuracy in Route Location. Traffic Quarterly, Jan. 1961.
6. Grant, E. L. Principles of Engineering Economy. pp. 44, 84-105. New York, Ronald Press, 1960.
7. Hewes, L. I., and Oglesby, C. H. Highway Engineering. pp. 41-74. New York, John Wiley and Sons, 1954.
8. Roberts, P. O., and Suhrbier, J. H. Highway Location Analysis, an Example Problem. M.I.T. Dept. of Civil Eng. Rept. R62-40, Dec. 1962.
9. Roberts, P. O., and Suhrbier, J. H. DTM Location System, Program Manual. M.I.T. Dept. of Civil Eng. Rept. R62-8, April 1962.

10. Roberts, P. O., and Villaveces, A. DTM Design System, 20K Program Manual. M.I.T. Dept. of Civil Eng. Rept. R62-6, Dec. 1961.
11. Roberts, P. O., and Currie, J. A. DTM Design System, 40K Program Manual. M.I.T. Dept. of Civil Eng. Rept. R62-7, Dec. 1961.
12. Currie, J. A. Volumetric Quantities, Program Manual. M. I. T. Dept. of Civil Eng. Rept. R62-9, March 1962.
13. Elias, Z. Preliminary Bridge Cost Analysis. M.I.T. Dept. of Civil Eng. Rept. R63-8, Dec. 1962.
14. Lang, A. S., and Robbins, D. H. A New Technique for the Prediction of Vehicle Operating Cost in Connection with Highway Design. M. I. T. Dept. of Civil Eng. Rept. 141, April 1961.
15. Lang, A. S., Robbins, D. H., and Roberts, P. O. Vehicle Simulation and Operating Cost System, Program Manual. M. I. T. Dept. of Civil Eng. Rept. R62-35, Sept. 1962.
16. Information Report on Road User Benefit Analyses for Highway Improvements. Washington, D. C., AASHO, 1960.
17. Ruiter, E. The Effects of Random Traffic on the Accuracy of the Vehicle Simulation and Operating Cost System. M. I. T. Dept. of Civil Eng. Rept. R63-3, July 1963.
18. Villaveces, A. Computer-Aided Plan Preparation for Highway Design. Unpubl. S. M. Thesis, M. I. T., Aug. 1962.

Use of Marginal Cost of Time in Highway Economy Studies

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This paper gives the preliminary results of a recent field study on the cost of passenger car time savings. The study, sponsored by the U. S. Bureau of Public Roads, was the outgrowth of a paper presented by Haney (14).

The major objective of the present study was to determine an appropriate hours-to-dollars conversion factor for analyses and evaluations of alternative highway locations and designs. Traffic projections, economy studies, and planning reports for current and future construction projects were examined in several states, and costs of road users' time savings were computed on two alternate bases: (a) using a state's own cost factors and assumptions (such as interest rates and length of study period), and (b) using a standard set of cost factors and assumptions, for comparability of the results between states. Rates of return and benefit/cost ratios were also derived in many cases, for comparison with the cost of time. The results were considered from the standpoint of improving the data available to state highway departments for decisions about construction project alternatives and priorities.

A set of procedures is also included for use by state highway departments desiring to experiment further with use of the cost of time as an added index of project desirability. A generalized procedural checklist for highway economy studies also is included, as a result of observations of certain errors and shortcuts in current state economy studies that could significantly affect their results.

•IT IS FREQUENTLY necessary for state highway agencies and other groups responsible for furnishing or evaluating transportation services to decide between the merits of competing investment proposals, either as to their relative priority in time or, if they are alternative routes, as to their relative superiority. The computations of investment, maintenance, and road user costs which often accompany such a decision represent an attempt to measure in dollars as many as possible of the tangible consequences of the competing proposals. Among the predicted consequences whose conversion to a dollar value has become accepted practice is the amount of passenger car time saved by each of the proposed investments. The passenger car hours-to-dollars conversion factor is known as the "value of time," or V.

In spite of general agreement that some value should be ascribed to passenger car time savings, the rather wide range of from \$1 to over \$4 per passenger car hour was found in references on the subject published since 1950 (15, pp. 22-23). There is an urgent need to narrow the range of uncertainty about the proper value or values of time to use in highway economy studies because of the relatively high percentage of total road user savings—usually 50 percent or more—that are due to the assumed value of passenger car time savings.

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Another feature of the value of time is the difficulty in ascribing "costs" in the usual economic sense to the time of passenger car occupants, since much of the time they save has not been shown to be marketable or to increase their monetary income. Indeed, the value of time is not ordinarily defined as a cost but rather as an intangible "willingness to pay." By such a definition, estimates of road user benefits which include the value of time savings are a composite of tangible dollar savings (in vehicle operating or running costs, truck time costs, and accident costs) and the intangible willingness on the part of passenger car occupants to pay for the time they would save on improved highways.

As an alternative or supplement to assuming a certain willingness-to-pay value of time, it is possible to obtain the minimum dollar value that one must relate to an hour of passenger car time in order to justify a proposed highway investment—that is, to achieve a benefit/cost ratio of 1 in comparison with an existing road or some alternative improvement. In a paper presented before the 1963 Highway Research Board meeting (14), Haney explored the theoretical problems involved in using this minimum acceptable dollar value of passenger car time, employing the term "cost of time" (C) to refer to the concept. In algebraic terms, the cost of time for a highway project is defined as follows:

$$C = \frac{\Delta h + \Delta m - \Delta u}{\Delta t} \tag{1}$$

where

C = cost of time ($/hr),
Δh = initial right-of-way and construction cost increment ($),
Δm = present worth of annual road maintenance cost increment ($),
Δu = present worth of road user savings in operating, truck, time, and accident costs ($), and
Δt = present worth of passenger car time savings (hr).

Derivation of the three incremental present worths (Δm, Δu, and Δt) is explained in the section "Present Worth Formulas" at the end of Appendix A. The formula for C is derived by solving for what might be called the "break-even" value of time, that makes the present worth of net future road user benefits equal to initial highway costs, or

$$\Delta h = \Delta u + V\Delta t - \Delta m \tag{2}$$

Solving for V:

$$V = \frac{\Delta h + \Delta m - \Delta u}{\Delta t} = C \tag{3}$$

where V = value of time, in dollars per hour.

Two major uses of the cost of time are described in this paper. First, the cost of time for individual highway projects is compared with the assumed value of time. If the cost of time is less than the assumed value of time, the project is desirable. Such a comparison is similar to the procedure of comparing the rate of return on an individual investment with some assumed "minimum attractive rate of return," in which a project is desirable if its rate of return is greater than the minimum attractive rate of return.

A second use of the cost of time is in establishing the value of time for analysis of an entire highway construction budget. Before explaining this process, two terms must be introduced:

1. If construction projects are ranked by increasing cost of time, the cost of time for the last project covered by a given construction budget is defined as the "marginal cost of time" for that budget.

2. When a value of time is used for economic evaluation of a set of projects, the value used is defined as the "maximum allowable cost of time" for the set, because projects with a higher cost of time will have benefit/cost ratios of less than 1.

As Haney demonstrated, since the choice of highway projects on economic grounds may vary with the value of time chosen and since little confidence can be placed in values of time in current use, it is essential to use the lowest value of time possible for analysis purposes; this value is the marginal cost of time for the highway construction budget. (Except that when the marginal cost of time is negative, V should be set equal to zero.) To take a numerical example, if the value of time in use by a particular state is \$1.50 per hour but the marginal cost of time for the state's future construction budget is estimated to be only \$0.75 per hour it would indicate that a maximum allowable cost of time as low as \$0.75 could still result in benefit/cost ratios of 1 or greater for all projects included within the future budget.

The cost-of-time approach to establishing a proper value of time for economic analysis is similar to the following procedure suggested by Roland McKean for handling the closely related problem of intangible benefits in water resource projects (22, p. 63):

> . . . it must be conceded that, if a project's outputs cannot be freely bought or sold or cannot even be accurately defined, the derivation of values for them is at best not wholly satisfying, and is at worst subject to serious abuse. We cannot prescribe just where to draw the line between effects which should be measured in terms of the common denominator and those which should not. [However,] . . .if both gains and costs are being expressed in dollars. . .it may be possible to show the minimum dollar value that one must attach to the intangibles if he prefers Project A over alternative investments.

The objectives of the present paper are to report on an effort to extend the use of the cost-of-time concept to evaluating actual highway construction projects in three states; to derive values for the marginal cost of time in these three states; and to explore the significance of the marginal costs of time so derived for general application in highway economy studies.

Throughout the paper, the basic economic criterion in selection of highway improvements within available construction budgets is to minimize the present worth of total highway transportation costs (initial right-of-way and construction costs + road maintenance costs + road user costs) using an appropriate interest rate, study period, and value of time. The most direct way of meeting this criterion is to select the set of projects that will maximize the present worth of savings in highway transportation cost. The cost of time, benefit/cost ratios, and rates of return are treated as "economic indexes" which when properly used can aid in selecting the economically optimal set of projects.

Many of the cost factors and procedures for road user benefit analysis that are set forth in the AASHO Redbook (1) have in effect been superseded by a variety of improved sources. However, differences of opinion and practice still exist on a number of important points of procedure. An effort has therefore been made in this paper to develop a fairly comprehensive statement of methodology, based on judgment as to the best available sources and authorities. It was also anticipated that this methodology might serve as a guide to states that wish to explore further the use of the cost of time in analysis or administration of their own highway construction programs. The assumptions and methods employed in the study are described in the next two sections of this paper, supplemented by Appendixes A and B. The two concluding sections of the paper describe the results of individual project analyses in the three cooperating states, and discuss the implications of these case studies for future highway economy studies.

PROJECT SELECTION CRITERIA AND ASSUMPTIONS

In order to limit comparisons to projects meeting generally similar quality standards, highway construction projects were chiefly selected from the Federal-aid primary (FAP) system, with a few examples from the interstate system and from major secondary roads. Projects selected had to have as their major purpose the speedup of future highway traffic either through building a new route or through significantly improving an existing route, as opposed to projects for such purposes as surface reconstruction or the elimination of road hazards. A "project" was defined as any discretely funded stage of a proposed highway improvement, so that independent links of a given improvement proposal could be evaluated separately. Because of the added complexity of analyzing truck speeds and benefits on steep grades, projects in hilly or mountainous terrain were excluded.

The following budgetary policy observations and assumptions were made for the present study:

1. Highway budgets are fairly well known for several years in advance because forecasts of gasoline taxes and other revenues can be made with reasonable accuracy. The total funds anticipated may be subdivided in various ways, such as along geographical, functional, or system lines; each such subdivision constitutes a separate constraint for advance planning purposes, and only construction projects within the same budgetary subdivision should be considered in direct competition with each other.

2. The major problems in highway priority determination lie beyond the current fiscal year and the subsequent fiscal year, since most construction projects for those two years will already have binding commitments. It is therefore the subsequent "advance planning program" on which priority determination should focus. For analysis purposes it appears most convenient to take successive 3- to 5-yr "budget planning periods" within, say, a 6- to 20-year advance planning program, and consider all potential construction projects in competition for funds within that period by setting the zero year for the economy studies midway in the budget planning period. Projects with less desirable ratings can then be considered for funding in the succeeding budget period, and so on to the end of the advance planning program.[1]

3. Very large projects, which have to be funded and constructed over a period of two or more fiscal years, may sometimes usefully be divided into sections for economic analyses. This may create problems with a project of moderate overall priority which contains some very high- and very low-priority sections; normally, the logical approach would be to schedule the high-priority sections early and either drop or defer the low-priority sections, unless the high-priority sections depend on the low-priority sections as traffic connections, feeders, or in some similar way. Such problems could be avoided if sections are chosen for analysis purposes that are relatively independent of each other physically. Highly interdependent sections must be considered together, as one project, for economy study purposes.

The foregoing budget policy assumptions are believed to correspond reasonably well with the way that most state highway agencies proceed with the development of their advance planning programs (except that economic analysis is not commonly a part of the priority determination process at present). Naturally, the farther off a given year is in the advance planning period, the more tentative and subject to change is the selection of projects for that year. Changes in scheduling as a remote year draws closer to the budget year will arise for many reasons—political, financial, workload leveling, etc.—but none of these changes negate the basic value of the advance planning program as an aid to orderly consideration of potential highway construction projects.

METHODOLOGY

General Comments

The five steps followed for the economic analysis of highway projects in each of the three states are summarized as follows:

[1] The question of optimum lengths of budget planning periods would profit from further research and experimentation. One consideration is that the longer the budget period used, the greater the risk that low-priority projects which have rapid growth rates and which are scheduled late in the period might in fact have significantly higher benefit/cost ratios if their zero years were located toward the end rather than at the middle of the budget period. Another consideration is the masking effect of multi-year budget periods on evaluation of incremental investments, explained later in the section, "Example of Postponement Analysis."

1. Compilation of basic project data, including estimation of any missing information;
2. Calculation of 1966 user costs and savings;
3. Expansion of 1966 user savings to 25 years (1966-1990), and calculation of incremental present worths (Δh, Δm, Δu, and Δt) at 6 percent interest;
4. Calculation of economic indexes: transportation cost savings, cost of time, benefit/cost ratio, and rate of return; and
5. Ranking of competing projects.

Appendix A contains a detailed discussion of steps 1, 2, and 3 which lead to the derivation of present worths for Δh (incremental initial cost), Δm (incremental maintenance costs), Δu (road user savings in operating, truck time, and accident costs), and Δt (passenger car time savings). It should be mentioned, however, that values for these four factors are normal outputs of highway economy studies, and if economy studies on a standardized basis were routinely conducted for all state highway construction projects, it would be a simple matter to use the output of the state studies for steps 4 and 5. The fact is that only the small proportion of highway projects that involve alternative routes are normally subjected to economy studies. Further, such a wide variety of techniques and assumptions are employed from one state to another that the results of economy studies in different states are rarely comparable. For example, variations exist in the length and zero year of the study period employed; in the rate of interest used; the values of passenger car or truck time and of operating cost factors; the inclusion of estimates for maintenance costs, resurfacing costs, and accident costs; and the inclusion of estimated benefits from speeding up traffic remaining on other unimproved roads following construction of a major new highway. Such differences affect, in varying degree, the benefit/cost ratios, cost of time, and rates of return that would be computed for a given project. As an example of such effects, Appendix B compares the results of a typical state economy study with the results from methods employed in this paper.

Steps 4 and 5, relating to the use of Δh, Δm, Δu, and Δt to obtain project priorities, involve several significant departures from present highway economy theory. These two steps are discussed next, in sequence.

Calculation of Economic Indexes

Formulas for economic indexes that were employed or considered for the cost-of-time study are listed below, using the symbols for present worth of increments defined in the introduction. The formulas are followed by brief comments on the uses and limitations of each one.

Cost of Time (dollars per hour): Eq. 1.

Rate of Return (percent): i at which Eq. 2 holds.

Transportation Cost Savings (dollars):

$$S = \Delta u + V\Delta t - \Delta h - \Delta m \tag{4}$$

Benefit/Cost Ratio:

$$R = \frac{\Delta u + V\Delta t - \Delta m}{\Delta h} \tag{5}$$

Present Value Ratio (or "Present Value per Dollar of Investment"):

$$P = \frac{S}{\Delta h} \tag{6}$$

The cost-of-time concept has already been defined as the actual cost of providing time savings on a specific project. In Eq. 1 for the cost of time, the difference (Δh + Δm - Δu) is the net increase in the present worth of transportation costs other than the value of passenger car time savings for a given project or project grouping. When the benefit/cost ratio for a given project is 1, the cost of time is equal to the assumed value of time, and when the benefit/cost ratio exceeds 1, the cost of time is less than the assumed value of time. Negative costs of time indicate that total highway costs ($\Delta h + \Delta m$) are more than offset by the present worth of user savings in operating costs, truck time costs, and accident costs alone (Δu).

Eq. 2 expresses the conventional method for finding the rate of return by trial-and-error solution in cases where a project's benefits can logically be assumed to be re-invested at its rate of return.

Eq. 4 for transportation cost savings simply gives, in present worths, the excess of incremental road user benefits over incremental highway costs. If S is zero or greater, the investment would be considered desirable.

The separate identification of Δm in these equations arises from the desirability of keeping annual maintenance costs out of the denominator of Eq. 5, the benefit/cost ratio. This problem has been discussed at length elsewhere (e.g., 13 and 22), but may be illustrated by the following simplified example: assume that the three nonmutually-exclusive projects X, Y, and Z are being considered for inclusion in a given budget, and that it is desired to rank them in order of priority by means of their benefit/cost ratios. Table 1 gives the pertinent data for each of the projects, in comparison with the existing highway at each site.

Since each project requires the same investment of \$10, the relative savings in transportation costs created by each project will be an index of the project's comparative desirability according to our basic criterion of minimizing the present worth of highway transportation costs within a given budget. It is evident from the transportation cost savings in line 5 of Table 1 that the three projects' relative order of economic merit is X, Y, Z, due to their respective savings of \$90, \$80, and \$72. However, a comparison using benefit/cost ratios with maintenance costs added to initial highway costs, as in line 6, will produce exactly the opposite ranking: Z, Y, and X. A correct ranking solution using benefit/cost ratios is possible by first deducting maintenance costs from future benefits (Table 2).

It has been argued in the past that the benefit/cost ratio is not appropriate for ranking a series of investments, and should only be used for comparing two alternative investments. In Table 1 the following results would be obtained from such a comparison (a) incremental benefits of X compared with Y = \$20, (b) incremental costs of X compared with Y = \$10, and (c) benefit/cost ratio of X compared with Y = \$20/\$10 = 2.0.

Table 1

COMPUTATION OF BENEFIT/COST RATIO BY USUAL METHOD

Item	X	Y	Z
1. Initial cost (Δh)	\$ 10	\$ 10	\$10
2. Maintenance (Δm)	\$ 20	\$ 10	\$ 2
3. Total cost (line 1 + line 2)	\$ 30	\$ 20	\$12
4. Benefits ($\Delta u + V\Delta t$)	\$120	\$100	\$84
5. Transportation cost savings (line 4 - line 3)	\$ 90	\$ 80	\$72
6. Benefit/cost ratio, usual method $\left(\frac{\text{line 4}}{\text{line 3}}\right)$	4.0	5.0	6.0

Table 2

COMPUTATION OF BENEFIT/COST RATIO WITH MAINTENANCE COSTS IN NUMERATOR

Item	X	Y	Z
1. Benefits ($\Delta u + V\Delta t$)	\$120	\$100	\$84
2. Maintenance (Δm)	\$ 20	\$ 10	\$ 2
3. Net benefits (line 1 - line 2)	\$100	\$ 90	\$82
4. Initial cost (Δh)	\$ 10	\$ 10	\$10
5. Benefit/cost ratio $\left(\frac{\text{line 3}}{\text{line 4}}\right)$	10.0	9.0	8.2

Granted that the foregoing incremental benefit/cost ratio of 2.0 correctly selects project X over project Y, the question may still be raised: is it not simpler and just as valid to rank projects X and Y by the method of Table 2? "Present value" analysis has been defended as an appropriate method of ranking corporate investment opportunities (e.g., 17, 20, and 24), and present value analysis is essentially the same comparison of future net income streams with initial investment as is illustrated for a highway investment in Table 2 where the present worth of the maintenance cost increment was deducted from the present worth of future highway benefits. Use of the benefit/cost ratio for ranking investments which include sets of mutually exclusive alternatives should of course be accompanied by an iterative procedure for handling the incremental investment in the mutually exclusive alternative sets. Such an iterative technique was demonstrated in the previous cost-of-time paper (14, Appendix A), and is described in the next section of this paper.

Aside from the use of benefit/cost ratios for ranking purposes, it seems intuitively more satisfying to have only the initial investment in the denominator. Each increase of 1 in the benefit/cost ratio can then readily be recognized as an additional return of 100 percent of the initial investment, and smaller changes in the ratio will have some consistent relative meaning in relation to the original investment. Also, if one's objective is (as we have assumed) to maximize the future excess of transportation benefits over transportation costs that will result from a present outlay, then the present outlay alone must appear in the denominator when the benefit/cost ratio is used as an index for ranking competing proposals. Otherwise, what is maximized will be the excess of transportation benefits over transportation costs that will result from the sum of a present outlay plus its future maintenance costs. Such a criterion will, as may be seen from Table 1, prejudice projects with high maintenance costs even though incremental future benefits are more than enough to offset the higher maintenance costs.

Eq. 6 for the present value ratio is in effect a variation of the benefit/cost ratio. The equivalence of Eq. 6 with Eq. 5 for the benefit/cost ratio is shown as:

$$P = \frac{S}{\Delta h} = \frac{\Delta u + V\Delta t - \Delta h - \Delta m}{\Delta h} = \frac{\Delta u + V\Delta t - \Delta m}{\Delta h} - \frac{\Delta h}{\Delta h} = \frac{\Delta u + V\Delta t - \Delta m}{\Delta h} - 1 \qquad (7)$$

but since:

$$R = \frac{\Delta u + V\Delta t - \Delta m}{\Delta h} \qquad (5)$$

therefore,

$$P = R - 1 \tag{8}$$

This result shows that the present value ratio is always one less than the benefit/cost ratio for a given investment. If a cutoff point of 1 is adopted for R, an equivalent cutoff point for P would therefore be zero; this is also the point at which transportation cost savings (the numerator of the present value ratio) would equal zero. Our purpose is not to debate the relative merits of the benefit/cost ratio and the present value ratio, but only to show that conclusions reached for either of the two indexes will also hold for the other, provided that both are computed in the manner suggested.

Ranking Competing Projects

Highway Economy Studies and Advance Programming. —It is desirable at the outset to consider the relationship of project-ranking procedures by highway economy methods to current methods of establishing priorities for competing state highway construction projects, since current state methods rely almost exclusively on noneconomic methods. The most widely used method of state highway priority determination is some variation of "sufficiency ratings" involving the comparison of several important road or traffic variables with assumed standards of adequacy on a numerical scale that is weighted subjectively according to the importance ascribed to each variable. Thus, the Tennessee method defines standards for "dependability," "facility of movement," and "safety" on a ten-point scale, and rates the relative sufficiency of each road section according to estimates of remaining surface life (for dependability), operating speed during the design hour (for facility of movement), and number of accidents per mile (for safety). The Tennessee Department of Highway's interpretation of the resulting three-number rating, insofar as priority determination for major highway improvements goes, places greatest emphasis on the facility of movement rating.

The following important parallels and contrasts exist between highway sufficiency rating procedures and the type of economic analysis of an entire highway construction program that is undertaken in this paper:

1. The results of either sufficiency ratings or economy studies may become part of the input to the extremely complex activity of "advance programming," as that activity is described by Granum and Burnes (31, p. 23).
2. Sufficiency ratings and economy studies both typically use basic highway data on speed, accident rates, and road resurfacing expectancy; but whereas sufficiency ratings convert the basic data into index numbers, economy studies convert the data into transportation costs or dollar equivalents.
3. Given two equally deficient sections of highway, and a budget limitation that prevents improvement of both sections at the present time, sufficiency ratings can make no contribution toward a decision between the two improvements, whereas the results of an economy study would help by giving the relationship of estimated dollar benefits to the estimated dollar costs of making each improvement.

The latter point appears to be seldom considered in making up lists of highway "needs," since lists of needs are typically based on achievement of certain road standards without specific regard to whether the costs of a particular highway improvement bear a reasonable relationship to the road user benefits obtained by the outlay.[2] Yet,

[2]For purposes of illustration, assume that road section M through a mountainous region is rated equally as deficient as a certain rural road section S, of equal length, through a rapidly growing suburban area. Section M could conceivably require several times the investment of section S to remove curves and grades, to add lanes for expected increases in traffic, or otherwise to improve the roadway to a predetermined level of sufficiency. How can the priorities of work on the two sections be compared, taking expected traffic loads and road user benefits into account? It may also be relevant to ask how the merits of different levels of improvement on one or both sections compare. Sufficiency ratings by themselves cannot cope with such questions.

very little additional data or time would be required to obtain economic indexes, once the information necessary for sufficiency ratings is at hand. It has been argued in the past that economy studies lack the precision necessary to use them for comparison of the alternative routes of a given project. However, economy studies should be at least as reliable as sufficiency ratings for such comparisons, especially if the resulting economic indexes are not taken as absolute indicators apart from intangible considerations not readily translatable into dollars.

The following five subsections of the paper describe the use of one economic index—the benefit/cost ratio—in highway economy studies. The subsequent subsection describes the use of other indexes.

Current Practices for Interpretation of Benefit/Cost Ratio. —The AASHO Redbook gives three inconsistent criteria for interpreting the benefit/cost ratios that result from highway economy studies, as follows:

Criterion 1

> To make analyses for two or more alternates of highway improvement a benefit ratio is calculated for each alternate compared to the basic condition. The indices for the several alternates indicate their relative merit as regards road user benefits. (1, p. 14)

Criterion 2

> A benefit ratio less than one indicates that in a road user benefit sense the basic condition is to be preferred over the alternate improvement. (1, p. 28)

Criterion 3

> There may be advantage where several alternate locations or designs are being compared in a second-step benefit ratio calculation to analyze the expenditure of capital cost with resultant gain in benefits. (1, p. 151)

Examples worked out in the AASHO Redbook generally follow Criterion 1, ignoring the other two criteria. For instance, Example 6 on pages 40-44 of the Redbook compares two levels of highway improvement termed "Plan 1" and "Plan 2," for which the financial data indicated in Table 3 are estimated.

The comparison of Plan 2 with Plan 1 shown in the final line of Table 3 is not given by the Redbook, which concludes its example with the statement that "It appears that Plan 1 is more desirable than Plan 2 and should be selected for construction." By Criterion 3, however, as illustrated in Appendix B of the Redbook, Plan 2 should have been chosen, since the extra cost of Plan 2 over Plan 1 would be more than offset by the incremental benefits of Plan 2 compared with Plan 1.

It is generally acknowledged, even though far from universally practiced, that comparison of incremental benefits and costs as suggested by the Redbook's Criterion 3 is the only appropriate method for economy studies. However, even the Redbook's Criterion 3 is not a complete statement of the criterion problem. A full description of proper investment criteria has to allow for projects in which the least-cost alternative has a benefit/cost ratio of less than 1; in such cases, the incremental benefit/cost ratio of the higher cost alternative is not relevant. A full statement of criteria must also distinguish between (a) the simple case where no budget constraint is involved, and (b) the more complex but considerably more common case of a fixed investment budget. Proper investment decision rules for these two cases are discussed in turn below.

Decision Rules for First Case: Two Alternatives and No Budget Constraint. —This case is similar to the Redbook's Example 6, discussed above, with a "least cost" alternative and a "higher cost" alternative. The three possible decisions are summarized in Table 4.

The left-hand column of Table 4 lists the three benefit/cost ratios that need to be obtained: the least cost and the higher cost alternatives versus doing nothing (ratios A and B), and the higher cost versus the least cost alternative (ratio C). Following the first two sets of benefit/cost ratios through the table: if ratio A is greater than or equal to 1, and ratio C is less than 1, the right decision is to do the least cost alternative; if ratio A is greater than or equal to 1, and ratio C is also greater than or equal to 1, the right decision is to do the higher cost alternative. In neither case is ratio B relevant to the question. As indicated, ratio B does become relevant when ratio A is less than 1. In that event, the higher cost project must stand on its own feet, so to speak. The decision will then be to do the higher cost alternative if ratio B is greater than or equal to 1, and to do nothing at all if ratio B is below 1.

One important observation is that although the decision rules in Table 4 are specified only for the case of a single project with two alternatives, the rules may readily be generalized to permit a ranking of any number of projects by comparing each project successively with all other projects, one comparison at a time. However, such a procedure becomes extremely burdensome for a large number of projects; for example, 25 to 50 projects had to be ranked in each of the three states visited for this study, and comparing each project with all other projects would have been quite time consuming. The abbreviated procedure described in the next section was used instead.

Decision Rules for Second Case: Ranking a Series of Projects Within a Limited Budget.—If all highway projects being considered for funding within a given budget period have only a single proposal for improvement, the economically optimum set of projects may be selected by simply ranking the projects in order of descending benefit/cost ratios until the budget is exhausted. The last project covered by the budget is defined as the marginal project, and its benefit/cost ratio as the marginal benefit/cost

Table 3

SUMMARY OF FINANCIAL DATA FROM
EXAMPLE 6 IN AASHO REDBOOK
(Dollars in Thousands)

	Annual Road User Costs	Annual Highway Cost
Existing roads	$5,730	$ 46
Plan 1	4,760	234
Plan 2	4,697	264

	Annual Incremental Benefits	Annual Incremental Costs	Benefit/ Cost Ratio
Plan 1 vs existing roads	$ 970	$188	5.2
Plan 2 vs existing roads	1,033	218	4.7
Plan 2 vs Plan 1	63	30	2.1

Table 4

INVESTMENT DECISION RULES FOR THE CASE OF TWO ALTERNATIVES AND NO BUDGET CONSTRAINT

Type of Benefit/Cost Ratio	Value of Benefit/Cost Ratio			
A. Least Cost vs Do-Nothing	>1.0		<1.0	
B. Higher Cost vs Do-Nothing	--	--	>1.0	<1.0
C. Higher Cost vs Least Cost	<1.0	≥ 1.0	--	--
Decision	Do Least Cost Alternative	Do Higher Cost Alternative		Do Nothing

Procedure

Step 1: Obtain the three types of benefit/cost ratios identified in the first column.

Step 2: Compare each ratio successively with a benefit/cost ratio of 1, moving vertically down the above table to the correct decision at the bottom. (Dashes in the table indicate that the type of benefit/cost ratio in question is not applicable.)

ratio. Of particular interest is the fact that the marginal benefit/cost ratio becomes the cutoff or decision point, rather than a benefit/cost ratio of 1 as in the previous case where no budget limitation was involved. In a continuing highway program, of course, the decision not to do a particular project in one budget period does not prevent its reconsideration in a later budget period. In a later budget period, the project will be in competition with a different (and possibly somewhat lower priority) set of projects than in the first period, and in addition, traffic increases over time may give the project a higher benefit/cost ratio when the ratio is calculated in a period later than the first period.

While a simple ranking of benefit/cost ratios will work for projects involving only one proposal for improvement, it is far more usual for some potential highway projects to involve at least two alternative routes or levels of improvement (plus the do-nothing case). In that event, the first step in the selection procedure is to compute benefit/cost ratios for each alternative of a project compared with all other alternatives of the same project (including the do-nothing condition). The second step or series of steps is to follow the iterative procedure described in the previous cost-of-time paper (14, p. 9), which involves the selection of projects and of incremental investments with successively lower benefit/cost ratios until the budget is exhausted. In the course of this process, lower cost project alternatives that were approved at a previous iteration may be displayed in a later iteration through approval of the incremental investment in a higher cost alternative. This event may be illustrated by reference to the Redbook's

Example 6 as summarized in Table 3: if the marginal benefit/cost ratio (the benefit/cost ratio for the last project covered by a given budget) is below the 2.1 incremental benefit/cost ratio of Plan 2, then the $30,000 additional cost of Plan 2 would be approved. Plan 1, with a benefit/cost ratio of 5.2, would have been approved at a previous iteration, but would now be displaced by Plan 2.

The third and final step in the selection process when some projects involve two or more alternative improvement proposals is to consider the economic desirability of postponing any projects with incremental investments which have benefit/cost ratios greater than 1 but less than the marginal benefit/cost ratio for the period under consideration. Again in terms of the Redbook example in Table 3, the question can be stated as follows: assuming a marginal benefit/cost ratio higher than the 2.1 incremental ratio of Plan 2, would it be better from an engineering economy viewpoint to postpone the whole project in the expectation that the marginal benefit/cost ratio for some future budget period would be below 2.1, thereby justifying Plan 2 at that future period?

To answer this question, it is first necessary to forecast the marginal benefit/cost ratios of succeeding budget periods. In the event that a long-term supply of projects with benefit/cost ratios above 2.1 but below 5.2 is anticipated, it will obviously not be profitable to postpone the entire project, because the lower cost alternative (Plan 1) has a benefit/cost ratio of 5.2. On the other hand, if the marginal benefit/cost ratio is expected to decline below 2.1 in some future budget period, it may be profitable to postpone the project in order to justify carrying out the more expensive Plan 2. To determine the economic advantages of postponement requires analysis of total tradeoffs in costs and benefits that will be caused by postponing Plan 2. A simplified but reasonably realistic example of such a "postponement analysis" follows.

Example of Postponement Analysis.—While the benefit/cost ratios of the Redbook's Example 6 will be retained in order to preserve some continuity of discussion, it will be most convenient to change the benefits and costs from the Redbook example. Accordingly, the following assumptions are given:

1. In a certain highway agency, the six prospective construction projects A, B, C, D, E, and F are being considered for funding. For each project, the least cost improvement is known as Alternative 1 and the next higher cost improvement (if any) as Alternative 2. The data on these projects are presented in Table 5. Project A has an Alternative 1 with an initial cost of $10 million and a mutually exclusively Alternative 2 with an incremental initial cost of $10 million (total of $20 million). The other five projects involve only the single Alternative 1, with an initial cost of $10 million in each case.

2. Alternative 1 of Project A has a benefit/cost ratio of 5.2 and Alternative 2 of Project A has an incremental ratio of 2.1—similar to the Redbook example in both instances. The other five projects have ratios of 4.0, 3.5, 2.0, 1.5, and 1.5. The highway agency anticipates a future supply of projects with benefit/cost ratios of at least 1.5 for many years to come.

3. The construction budget for the highway agency is $20 million for the next three budget periods, which means that two $10 million projects or one $20 million project can be funded in each budget period.

Given the foregoing facts, a highway economy analyst proceeds to rank the projects in order of priority, by budget period. He notes that Projects B through F need simply to be scheduled in order of declining benefit/cost ratios, but that two choices exist with respect to Project A: it can either be undertaken at the $10 million level in the first budget period, or postponed until the second budget period, at which time the 2.1 incremental benefit/cost ratio of its Alternative 2 will exceed the 2.0 marginal benefit/cost ratio anticipated for the second budget period. The analyst makes a summary (Table 6) of the effect of the foregoing choices on total benefits in each budget period, throwing in for good measure a summary of benefits from doing Alternative 2 of Project A in the first budget period.

It is evident from Col. 5 of Table 6 that there are three significant economic effects of postponing Project A until the second budget period and doing the more costly alternative: (a) a \$17 million loss of benefits in Period I, (b) an \$18 million gain of benefits in Period II, and (c) a \$5 million gain of benefits in Period III.

Assuming that the budget periods are each one year in length, conversion of the gains of Periods II and III to equivalent present worths at 6 percent interest gives a total equivalent gain of \$20.2 million in Period I. Taking the \$20.2 million equivalent gain

Table 5

BASIC DATA FOR ANALYZING POTENTIALLY POSTPONABLE HIGHWAY INVESTMENT
(Dollars in Millions)

Project	Alternative	Incremental Benefits	Incremental Costs	Benefit/Cost Ratio
A	1	\$52	\$10	5.2
	2	21	10	2.1
B	1	40	10	4.0
C	1	35	10	3.5
D	1	20	10	2.0
E	1	15	10	1.5
F	1	15	10	1.5

Budget Period	Available for New Construction
I	\$20
II	20
III	20

Table 6

BENEFITS FROM THREE OPTIONS
(Millions of Dollars)

Budget Period	Option 1	Option 2	Option 3	Gain (+) or Loss (-)	
	Do A1 in Period I	Do A2 in Period II	Do A2 in Period I	Col. (2) - Col. (3)	Col. (3) - Col. (4)
(1)	(2)	(3)	(4)	(5)	(6)
I	\$92	\$75	\$73	\$-17	\$-2
II	55	73	75	+18	+2
III	30	35	35	+5	--

as "benefits" and the $17 million loss of benefits in Period I as "cost," a benefit/cost ratio of $20.2 ÷ $17.0 or approximately 1.2 is obtained. The ratio is close to but nevertheless greater than 1, and the analyst may therefore assert that there is a slight economic case in favor of Option 2—delaying Project A by a year in order to carry out its more expensive alternative.

It is of interest to observe that different results will be obtained in this example if the budget periods are assumed to be 5 years in length instead of 1 year. Discounting the gains in Periods II and III at 6 percent interest then results in an equivalent present worth in Period I of only $16.2 million, which is less than the $17 million loss of benefits in Period I (assuming end-of-period gains and costs in all cases).

Generalizing from this conclusion, it appears that the longer a project must be postponed in order for the incremental costs of its more expensive alternatives to be justified, the less likely is the postponement to be economically defensible.

A further observation on the postponement example is that Col. 6 of the summary of benefits shows there is no economic advantage in funding the higher cost Alternative A2 in Period I, compared with funding it in Period II (since the gain of $2 million in Period II will be less than the loss of $2 million in Period I, when discounted to an equivalent present worth).

Combination of the three budget periods used in the example into a single period with a total fund availability of $60 million would have a masking effect on the data given in Table 6, because the projects would then be evaluated on the basis of the same study period with the same zero year, and the three options given in Table 6 would no longer exist. The masking effect of combining three 1-yr budget periods into a single budget period is not significant, because the same conclusion would be reached in either case: do Alternative A2 instead of A1. However, as noted in the previous paragraph, if the original budget periods are each 5 years long, the proper decision based on separate budget periods would be to do project Alternative A1; but the decision based on a combined 15-yr budget period would be to do Project A2. The conclusion suggested by this brief example is that the larger the number of years that is combined into a single budget period, the greater is the risk that masking will result in the approval of economically undesirable incremental investments. Pending further research on the optimum length of budget periods for investment programs of various types and sizes, the tentative position has been taken in this study that periods of from three to five years in length are appropriate for the state highway construction programs under consideration.

Assessment.—It may perhaps be objected that the foregoing example of a postponement analysis assumes more knowledge of the future on the part of the analyst than it is reasonable to expect. For instance, what if projects with benefit/cost ratios of 2.5 and greater crop up in the second budget period, unforeseen until the decision to postpone Project A2 has been made? One possible reply to this objection is that all economic analysis is based on assumptions about future events, and decisions must be reevaluated when the predictions on which they were based turn out to be significantly erroneous. The firmness of commitments to the planned time schedule and design for a project usually increases with the proximity of the project, but until the actual construction contracts are let, a significant degree of flexibility may still remain in the hands of administrators to adapt the highway design and schedule to important changes in the estimates on which the advance planning program was based.

Speaking more generally about the entire procedure of selecting projects by their benefit/cost ratios, it must be clearly understood that an economic ranking of projects is only as valid as the estimates underlying the economy studies, especially the estimates of value of time, average daily speeds, opportunity cost of capital, and initial highway cost. Due care needs to be exercised to use the most reliable sources for these important variables, but engineering precision cannot be expected. A caution should also apply to the interpretation of intangibles and "spillover" costs connected with highway construction projects, since it is the job of the engineering economy analyst to identify any intangibles and spillover costs that influence the desirability of the project. A ranking by economic desirability has no validity until the differences between projects that cannot be converted into dollars are taken into account in some way in the decision-making process. Techniques for taking intangibles and spillover costs into consideration are discussed elsewhere (22 and 34, for example).

Possible Alternative Ranking Indexes.—While an exhaustive discussion of alternative procedures for ranking a set of potential investments is beyond the scope of this paper, it may be useful to compare briefly other possible methods with the benefit/cost ratio method just described. Such a comparison is presented in Table 7.

Table 7

COMPARISON OF OTHER POSSIBLE ECONOMIC RANKING INDEXES WITH THE BENEFIT/COST RATIO

Index	Comment
1. Cost of time	Ranking by the cost of time would result in selecting the same set of projects as would ranking by the benefit/cost ratio if V is set equal to the marginal cost of time for the given budget, but the projects would not necessarily be ranked in the same order.
2. Rate of return	**Ranking by the rate of return would always result in selecting the same set of projects as would ranking by the benefit/cost ratio method only if the marginal rate** of return happened to coincide with the interest rate used to compute benefit/cost ratios. Even so, projects included in the two sets would not necessarily be ranked in the same order. A difficulty with ranking projects by their rates of return is that benefits accruing to road users may be reinvested at the market interest rate, rather than at the rate of return, as is implied by the rate-of-return method. This problem is discussed in Annex A.
3. Payout period*	**Ranking by payout periods, from shortest to longest, would always produce the same set of projects as the benefit/cost ratio ranking only if the marginal payout period happened to coincide with the study period used in the benefit/cost ratio analysis. Even so, projects in-**cluded in the two sets would not necessarily be ranked in the same order.
4. Present value ratio	As already indicated, the "present value per dollar of investment" index is equivalent in every way to the benefit/cost ratio, and when properly used, should produce the same ranking and set of projects as the benefit/cost ratio.
5. Transportation cost savings	While maximization of transportation cost savings within an available budget is a useful general criterion, selecting individual projects by their absolute amount of transportation cost savings is inappropriate because the size of transportation cost savings by itself gives no indication of the relative initial investment required to produce the given savings.

*** Defined here as the time required for the present worth of net future benefits to equal initial costs.**

RESULTS OF FIELD STUDIES

General Information on Highway Systems Included in Study

The three areas included in this study were a single highway district in California, the entire state of North Carolina, and the entire state of Tennessee. The general characteristics of these three sets of highway construction projects are noted briefly.

District IV of California's 11 highway districts covers nine counties in the rapidly growing San Francisco Bay Area. Nearly all major highway construction in the district is of freeways, many through suburban or urban areas, with complete access control planned either initially or in stages. A few expressways are programmed, with only partial control of access, for low-volume highway sections. As of January 10, 1963, District IV maintained a 7-yr advance planning program in addition to the budget year of FY 64; for this study, the total 8-yr span was divided into two 4-yr budget planning periods. The District had programmed some \$90 to \$110 million annually over the 8-yr period for right-of-way and construction expenditures, for a total of about \$840 million. Of this total, about \$508 million was programmed for the FAP rural and urban highway systems. The 28 District IV projects studied were chosen chiefly from the FAP rural and urban highway systems, and represented total initial costs of \$484 million.

A tabulation of the foregoing type of information for District IV, compared with similar data for North Carolina and Tennessee, is presented in Table 8. It is evident from Item 4b of the table that the majority of projects studied in each area were from the FAP rural and urban systems. The table also shows that the location and type of highways represented by the projects (Items 4c and d) vary somewhat from one state to the next, reflecting in part the differences in population density, terrain, and historical factors in each area studied.

Project Numbering System

Projects in California and North Carolina are numbered according to the fiscal year in which construction is to be initiated (e.g., 4.1, 4.2 for FY 64 projects, and 5.1, 5.2 for FY 65 projects). Projects in Tennessee, however, are numbered according to the geographical division of the state highway system (e.g., 1.1, 1.2 for Division 1, and 2.1, 2.2 for Division 2). The full project number also includes the following code symbols: (a) C = California, N = North Carolina, and T = Tennessee; (b) number of project (already explained), and (c) When more than one alternative to the existing condition is proposed for a given project, the number 1 is added to indicate the first alternative, 2 the second alternative, 3 the third, and so on (each compared with the existing condition). Two-digit numbers of the type 2-1, 3-1, 3-2, etc., are added to identify the incremental investments required for higher cost alternatives compared with lesser cost alternatives.

To illustrate the project numbering system by two examples, "N4.5" indicates the fifth North Carolina project scheduled for initiation of construction in FY 64, and "T3.2" indicates the second Tennessee project located in Division 3. Both of these examples involve only one alternative improvement; if the Tennessee project had two alternatives, the possible sets of economic data on the project would be identified as follows:

Code	Meaning of Last Two Digits
T3.2.1	Alternative 1 (least cost) compared with existing or do-nothing condition
T3.2.2	Alternative 2 compared with existing condition
T3.2.2-1	Alternative 2 compared with Alternative 1

Table 8

COMPARATIVE DATA ON HIGHWAY PROJECTS
INCLUDED IN STUDY, BY STATE
(Dollars in Millions)

	District IV, California	State of North Carolina	State of Tennessee
1. Length of budget planning period used (beginning with FY 64)	Two 4-year periods	3 years	5 years
2. SRI estimate of right-of-way and construction funds available during budget planning periods (including 10% for engineering and contingencies):			
a. Total, all highways	$840	$225	$550
b. Total, FAP rural and urban	$508	$ 93	$110
3. Total initial cost of projects studied	$493	$ 65	$ 83
4. Number of projects studied:			
a. Total	28	25	54
b. By system:			
Interstate	3	4	---
FAP rural and urban	23	16	53
Federal aid secondary	2	5	1
c. By location:			
Rural	5	8	27
Suburban*	15	4	11
Urban	3	2	8
Urban bypasses	5	11	8
d. By type of highway:			
Freeways	25	15	3
Expressways	2	1	13
Conventional	1	9	38

* Designation for the transitional zone between rural and urban locations, usually consisting of residential or industrial areas, where highway traffic is characterized by a high percentage of trips between home and work.

In the text, to facilitate locating projects in long lists, references to projects will usually be by the number representing the project's rank at V = \$1.80 in the tabulations (for example, "Projects No. 7, 8 and 15").

California Projects

The basic data, present worths, and economic indexes for projects in California Highway District IV are summarized in Table 9. Two of the 28 projects listed involve alternative route studies, and the incremental costs and other data for the alternative routes are also included in the listing, making a total of 31 items.

The basic project data presented in Table 9 are the most essential items of information: the general location and type of the project, indicated by the two-letter code in Col. 2; the length and ADT estimates in Cols. 3 through 5; the passenger car speed estimates in Cols. 6 and 7; and the initial cost in Col. 8. More complete data would be needed to appraise these projects fully—for example, it is useful to know that project No. 10 in the list is the 6- to 10-lane Junipero Serra Freeway, running from San Francisco to San Jose; that its construction has been studied over a period of some 20 years but was postponed until 1964-68 due to such difficulties as obtaining route agreements from intervening towns; that the Bayshore Freeway on the east side of the San Francisco Peninsula is rapidly approaching its capacity; and that there are no present plans for rapid transit services in the area between San Jose and San Francisco. Such facts are necessary to highway scheduling decisions, but are too lengthy for inclusion in this paper, which will have to be confined largely to a consideration of the economic factors that should affect the scheduling process.

In order to consider the essential problems of selecting a set of the projects in Table 9 within a given budget limitation without spending too much time on the mechanical details, a few assumptions need to be made:

1. The budget limitation will be as the amount available for all approved projects over the eight years FY 64-71, thus excluding the initial costs of the five projects scheduled beyond FY 71 (numbers C2.1 through C2.5 in Table 9). The total budget limitation thus derived is \$430.7 million; this figure will be divided into a limitation of \$215.4 million for Period I (FY 64-67), and \$215.3 million for Period II (FY 68-71).

2. It will be assumed that design, right-of-way purchases, and construction of each project can be completed within the 4-yr budget period out of which it is financed, although many of the projects studied were actually scheduled over periods of more than four years.

3. Highway projects involve discrete and usually large initial outlays of cash. These characteristics, sometimes described as "lumpiness," make it improbable that the cumulative initial costs of approved projects will exactly match a given budget limitation. In such cases, the initial costs and benefits of the marginal project will be allocated between budget periods on a pro rata basis. (For example, assume that the budget limitation for Period I is \$100 million, that projects previously selected will cost \$95 million, and that the marginal project on the priority list will cost \$10 million and involve net future benefits with an equivalent present worth of \$30 million. The rule just explained would cause \$5 million of that project's cost and \$15 million of its benefits to be allocated to Period I, and the remainder of its costs and benefits to Period II.)

Based on the foregoing assumptions and the data in Table 9, it is possible to prepare the economic rankings of the California projects for Period I shown in Table 10. It is apparent from the first three columns of Table 10 that a ranking at V = \$1.80 per hour will tentatively include the first 13 projects plus a portion of the 14th, to make up the budget limitation of \$215.4 million. A question must be raised, however, about Project No. 2. The incremental investment in the

Table 9

SUMMARY OF DATA ON SELECTED HIGHWAY PROJECTS IN CALIFORNIA

Project	Basic Project Data							Present Worths (x 10^6)			Economic Indexes				
	Loc. & Type	Lgth. in Miles	ADT (x 10^3)		1980 Avg. Daily PC Speeds		Δh (x 10^6)	Δm	Δu	Δt	Cost of Time	V=$1.80		V=$0.90	V=0
			1966	1980	Without Project	With Project						R	Rate of Return	R	R
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
1. C7.2	RE	3.7	13.8	30.5	28	57	$ 1.9	$0.19	$ 15.0	7.6	$-1.68	14.8	72.1%	11.2	7.6
2. C2.3.1	BF	9.3	8.3	18.8	27	58	4.3	0.43	30.1	14.0	-1.81	12.8	62.2	9.8	6.9
3. C4.2	BF	2.2	16.1	23.4	21	52	1.9	0.11	10.6	5.8	-1.50	11.2	70.8	8.4	5.6
4. C2.5	BF	3.3	15.0	20.0	28	40	2.0	0.09	13.6	2.8	-4.16	9.2	61.6	8.0	6.7
5. C4.4	SF	5.5	27.6	50.0	23	51	11.9	0.28	61.4	26.5	-1.86	9.2	52.0	7.2	5.1
6. C6.3	SF	1.4	21.8	39.3	21	51	2.6	0.08	11.3	5.8	-1.48	8.2	47.3	6.2	4.3
7. C5.4	SF	2.3	24.8	49.5	27	51	4.4	0.11	22.3	7.0	-2.53	7.9	43.8	6.5	5.0
8. C8.1	SF	1.8	12.9	35.1	27	55	2.4	0.09	10.5	4.1	-1.99	7.5	37.3	6.0	4.4
9. C1.3	RE	5.6	8.1	16.4	30	50	2.4	0.23	8.4	4.6	-1.25	7.0	38.5	5.2	3.5
10. C4.5	SF	46.1	40.0	74.4	27	54	158.8	4.01	620.1	257.8	-1.77	6.8	39.4	5.3	3.9
11. C6.1	SF	3.0	19.2	35.8	28	55	4.8	0.06	19.1	6.9	-2.05	6.5	37.9	5.2	4.0
12. C1.1	SF	5.8	8.5	21.0	28	58	5.5	0.20	20.6	8.2	-1.81	6.4	33.3	5.0	3.7
13. C7.1	SF	4.4	20.3	43.7	28	55	10.9	0.29	44.1	13.7	-2.40	6.3	34.6	5.1	4.0
14. C4.3.1	SF	10.6	16.4	38.0	28	57	18.5	0.61	71.1	23.2	-2.24	6.1	32.7	5.0	3.8
15. C5.3	SF	5.6	16.2	44.2	28	56	10.8	0.38	38.7	15.2	-1.81	6.1	31.1	4.8	3.6
16. C6.2	RC	1.0	10.9	19.1	28	58	0.9	0.04	2.9	1.4	-1.39	5.8	34.8	4.4	3.1
17. C1.2	SF	2.5	13.3	22.7	28	57	3.9	0.10	12.5	3.6	-2.34	4.9	30.5	4.1	3.2
18. C2.1	SF	4.4	10.4	20.0	28	58	7.5	0.19	23.2	7.3	-2.12	4.8	26.7	3.9	3.0
19. C4.1	UF	6.5	72.0	118.4	17	51	77.2	0.66	138.3	92.8	-0.65	4.0	25.4	2.9	1.8
20. C5.2	RF	4.7	12.6	23.1	28	57	10.1	0.24	24.3	8.6	-1.62	3.9	24.4	3.1	2.4
21. C1.4	RF	5.2	14.4	20.0	38	58	4.7	0.20	11.0	3.8	-1.62	3.7	25.4	3.0	2.3
22. C5.1	SF	1.2	17.9	40.0	25	54	2.5	0.06	4.1	3.0	-0.51	3.7	22.1	2.6	1.6
23. C7.3	BF	2.5	24.2	41.8	36	54	6.1	0.07	16.3	3.5	-2.89	3.7	23.6	3.2	2.7
24. C6.5	BF	5.0	7.9	12.6	30	58	5.1	0.26	10.5	4.3	-1.18	3.6	22.8	2.8	2.0
25. C6.4	UF	3.9	45.0	71.2	17	51	62.1	0.40	81.9	45.5	-0.43	2.6	17.8	2.0	1.3
26. C2.2	SF	1.4	14.5	28.1	28	56	5.2	0.06	8.6	2.4	-1.39	2.4	16.0	2.0	1.6
27. C2.3.2-1	BF	9.2	8.5	19.3	27	58	0.6	0.05	0.8	0.3	-0.66	2.1	13.4	1.7	1.3
28. C7.4	SF	1.2	27.9	60.0	17	53	20.0	0.09	16.4	9.7	+0.38	1.7	11.4	1.2	0.82
29. C2.4	UF	4.1	20.0	30.8	20	58	43.0	0.32	36.7	16.5	+0.40	1.5	10.4	1.2	0.85
30. C4.3.3-1	SF	0.1	0.4	0.9	28	57	1.3	0.01	1.2	0.1	+0.82	1.1	6.7	1.0	0.9
31. C4.3.2-1	SF	1.1	-1.2	-2.8	28	57	1.2	0.06	-11.2	-3.0	+3.28	-13.5	*	-11.7	-9.4

Location	Type
R = rural	F = freeway
S = suburban	E = expressway
U = urban	C = conventional road (no control of access)
B = urban bypass	

Other symbols are defined as follows:

PC = passenger cars
Δh = initial cost increment
Δm, Δu, and Δt = incremental present worths of maintenance costs; user savings in operating, truck time, and accident costs; and passenger car time savings
V = value of time
R = benefit/cost ratio

Economic indexes may not agree in detail, due to rounding. For example, in project #30, the benefit/cost ratio at V=$0.90 has been rounded from 1.01 to 1.0.

* Negative rate of return.

more costly alternative of this project is listed as No. 27 in Table 9, with an incremental benefit/cost ratio of 2.1 compared with a benefit/cost ratio of 12.8 for No. 2, the minimum investment.

These facts would place the priority of the incremental investment of $600,000 in No. 27 some eight years later than the minimum investment of $4,300,000 in Project No. 2. Also, it seems reasonable to assume that additional construction projects with benefit/cost ratios higher than the 2.1 ratio of No. 27 will occur in the meantime, further displacing the priority of No. 27. A more detailed postponement analysis for Project No. 2 does not therefore seem necessary, and the appropriate recommendation by an engineering economy analyst would be that there is a fairly strong economic argument for approving Project No. 2 in Period I, rather than doing the second alternative late in Period II.

Consideration must also be given to postponement of the marginal project (No.14) in the V = $1.80 listing. The two more expensive alternatives of the marginal project are at the bottom of the Table 9 project list (No. 30 and No. 31), with incremental benefit/cost ratios at V = $1.80 of +1.1 and -13.5. It may therefore be concluded (by the same reasoning that was applied to Project No. 2) that the minimum-cost improvement of the marginal project should be initiated in Period I rather than waiting until Period II to do the more expensive alternatives.

In order to compare the results of rankings made using several different values of time, Table 10 includes rankings obtained at V = $1.80, V = $0.90, V = 0, and ranking by the cost of time. The ranking by the cost-of-time method identifies -$1.77 as the marginal cost of time, and the set of projects selected is therefore the same (although not necessarily in the same order) as would be selected by the benefit/cost ratio method with V = -$1.77. Keeping this fact in mind, it is clear that Table 10 identified the sets of projects that would be obtained using progressively lower values of time, from + $1.80 to -$1.77.

The following differences from the V = $1.80 set of projects may be noted in the sets of projects obtained by the other rankings in Table 10:

	Ranking by B/C Ratio		Ranking by
	V = $.90	V = 0	Cost of Time
Projects eliminated from V = $1.80 set by indicated method	None	# 9 #12	# 1 # 3 # 6 # 9
Projects added to approved set by indicated method	None	#14 (portion)	#14 (portion) #15 #17 #18 #23

The tabulation indicates that larger numbers of differences from the set of of projects selected at V = $1.80 occur as the value of time used for ranking the projects in Period I grows progressively lower. In order to explore the reason for these changes in the set of approved projects, the variation of benefit/cost ratios with value of time for several projects listed in the foregoing tabulation is shown graphically in Figure 1. Projects that tend to be eliminated from the approved set with smaller values of time are shown as solid lines, and projects that tend to be added to the approved set with smaller values of time are shown as dashed lines. Note that the solid lines have a steeper slope, indicating a heavier dependence on time savings. This conclusion is supported by the following comparison:

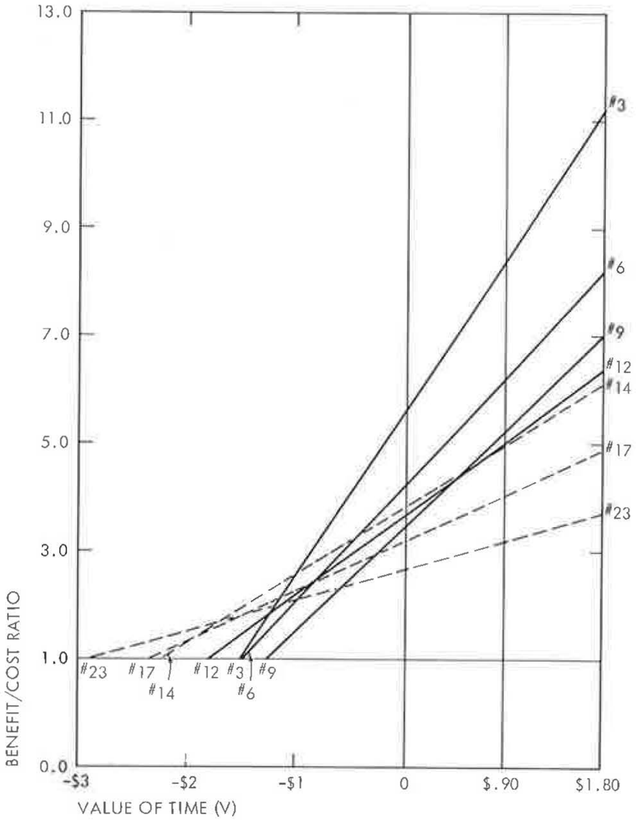
Solid Line Projects	Percentage of User Benefits Due to Passenger Car Time Savings	Dashed Line Projects	Percentage of User Benefits Due to Passenger Car Time Savings
#3	49.4%		
#6	48.0	#14	37.0%
#9	49.8	#17	34.4
#12	41.8	#23	27.9

The most striking characteristic of Figure 1 is the gradual displacement of the solid-lined projects by the dashed-line projects as the value of time used in the benefit/cost ratio decreases.

The question now arises: given the fact that different projects are selected for Period I at different values of time, what value of time should be defended as the most appropriate according to cost-of-time principles? To answer this question, it is necessary to consider the cumulative savings of Δt (passenger car time) and the cumulative net savings in transportation costs other than value of time savings (Δu - Δh - Δm) that would be achieved by each set of projects. These data are presented in Table 11.

Since the project set selected at V = \$0.90 is the same as the set selected at V = \$1.80, data for these two sets have been shown together in line 1 of Table 11. Note that in going from the V = \$1.80 or \$0.90 set in line 1 to the V = 0 set in line 3, an additional savings of \$1.6 million is achieved in net transportation cost. The price for these added user savings is a sacrifice of 2.9 million hours of passenger car time. Dividing \$1.6 million by 2.9 million hours, we obtain \$0.55 per hour as the break-even value of time. If passenger car time savings are assumed to be worth exactly \$0.55 an hour, it will be a matter of indifference which set is selected, and if time is valued above \$0.55 an hour, the V = \$1.80 or \$0.90 set would be selected.

These results are supported by the graphic presentation in Figure 1 of some of the projects dropped and added between the V = \$0.90 and V = 0 sets. Note that in the figure, Projects 9 and 12 become less attractive than Project 14 at about a \$0.50 value of time.



NOTE: Identifying numbers refer to project ranking in Table 10 at V = \$ 1.80/ hr.

Figure 1. Varying sensitivity of selected California projects to the value of time used in the benefit/cost ratio.

Table 10

ECONOMIC RANKINGS OF CALIFORNIA PROJECTS FOR BUDGET PERIOD I

Ranking by Benefit/Cost Ratios									Ranking by Cost of Time		
V=$1.80			V=$0.90			V=0					
Project (1)	R (2)	ΣΔh (x 10^6) (3)	Project (4)	R (5)	ΣΔh (x 10^6) (6)	Project (7)	R (8)	ΣΔh (x 10^6) (9)	Project (10)	C (11)	ΣΔh (x 10^6) (12)
1. C7.2	14.8	$ 1.9	1.	11.2	$ 1.9	1.	7.6	$ 1.9	4.	$-4.16	$ 2.0
2. C2.3.1	12.8	6.2	2.	9.8	6.2	2.	6.9	6.2	23.	-2.89	8.1
3. C4.2	11.2	8.1	3.	8.4	8.1	4.	6.7	8.2	7.	-2.53	12.5
4. C2.5	9.2	10.1	4.	8.0	10.1	3.	5.6	10.1	13.	-2.40	23.4
5. C4.4	9.2	22.0	5.	7.2	22.0	5.	5.1	22.0	17.	-2.34	27.3
6. C6.3	8.2	24.6	7.	6.5	26.4	7.	5.0	26.4	14.	-2.24	45.8
7. C5.4	7.9	29.0	6.	6.2	29.0	8.	4.4	28.8	18.	-2.12	53.3
8. C8.1	7.5	31.4	8.	6.0	31.4	6.	4.3	31.4	11.	-2.05	58.1
9. C1.3	7.0	33.8	10.	5.3	190.2	11.	4.0	36.2	8.	-1.99	60.5
10. C4.5	6.8	192.6	9.	5.2	192.6	13.	4.0	47.1	5.	-1.86	72.4
11. C6.1	6.5	197.4	11.	5.2	197.4	10.	3.9	205.9	2.	-1.81	76.7
12. C1.1	6.4	202.9	13.	5.1	208.3	14.*	3.8	215.4	15.	-1.81	87.5
13. C7.1	6.3	213.8	12.	5.0	213.8				12.	-1.81	93.0
14.* C4.3.1	6.1	215.4	14.*	5.0	215.4				10.*	-1.77	215.4

Note: V = value of time; R = benefit/cost ratio; ΣΔh = cumulative initial cost increment; C = cost of time. The complete project number is given in column (1); columns (4), (7), and (10) list only the number identifying the rank order of the projects in column (1).

* The following dollar amounts and percentages of the initial costs of the marginal projects have been included in Budget Period I: at V = $1.80 and V = $0.90, $1.6 million or 8.65%; at V = 0, $9.5 million or 51.4%; and in the cost of time ranking, $122.4 million or 77.1%.

Table 11

SAVINGS ACHIEVED BY ALTERNATIVE SETS OF CALIFORNIA PROJECTS
SELECTED FOR BUDGET PERIOD I
(Hours and Dollars in Millions)

	$\Sigma\Delta t$	$\Sigma(\Delta u - \Delta h - \Delta m)$
1. V=$1.80 or V=$0.90 set	366.8 hr	$671.4
2. V=0 set	363.9	673.0
3. Increase (+) or decrease (-) from line 1 to line 2	-2.9	+1.6
4. Cost of time set	334.7	639.9
5. Increase (+) or decrease (-) from line 2 to line 4	-29.2	-33.1

Note: $\Sigma\Delta t$ = cumulative savings of passenger car time (hours)
$\Sigma(\Delta u - \Delta h - \Delta m)$ = cumulative net savings in transportation costs other than the value of time savings

An analyst cannot go much beyond this point in a cost-of-time evaluation of alternative projects sets. The decision as to whether $0.55 an hour—or any other break-even point—is above or below the appropriate value of time should be left to the highway administrator. What the analyst can and should tell him is the range of time values over which a recommended set of projects would be consistently selected by the benefit/cost criterion.

All the details given in this illustrative case need not accompany the presentation of such information to the administrator, but there should be some attempt to make a reasonable assessment of the importance and reliability of the facts presented. In this case the benefit/cost ratios of Projects No. 9, No. 12, and No. 14 are fairly close at all values of time between 0 and $1.80/hr. It might, therefore, be appropriate to re-check the estimates of average speed or other critical data for these three projects, or at least to point out that even at V = 0, the economic case for displacing Projects No. 9 and No. 12 from Period I to Period II is not a strong one.

As a check on the rate-of-return method of ranking, the California projects were ranked by their rates of return at V = $1.80 (Col. 14, Table 9). The result, compared with the benefit/cost ranking, was displacement from the approved set of projects of a portion of Project No. 14 by Project No. 16. The total time savings achieved by the rate-of-return set were 0.24 million hours greater, but the net savings in transportation costs were $0.63 million less, indicating a break-even value of time of about $2.62 between the two sets. The added time savings achieved by the rate-of-return set would, therefore, have to be valued at $2.62 per hour or greater to justify selection of the rate-of-return set in preference to the benefit/cost set. This conclusion further supports the advisability of using benefit/cost ratios as the basic ranking device—but it is worth noting that the rate-of-return ranking does in this case rather closely parallel the benefit/cost ranking.

To return to Table 11, it is important to note from line 5 that the set of projects obtained by the cost-of-time ranking results in substantial reductions of both time

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SUMMARY OF DATA ON SELECTED P

Project	Basic Project Data						
	Loc. & Type	Lgth. in Miles	ADT (x 10^3)		1980 Avg. Daily PC Speeds		Per Mi in
			1966	1980	Without Project	With Project	Signal
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1. N6.6	BF	19.0	6.8	11.0	29	58	2.0
2. N4.12	RF	11.2	9.4	15.7	27	58	2.0
3. N4.9	RF	8.5	6.9	12.0	27	58	2.0
4. N4.5	SC	5.5	9.2	13.3	29	39	1.0
5. N4.8	RF	8.7	7.1	12.0	42	56	--
6. N5.5	SF	5.0	17.1	28.0	27	52	2.0
7. N4.10	RF	11.6	12.3	21.4	27	58	2.0
8. N6.1.2	BF	6.1	5.5	8.0	27	52	2.0
9. N4.3	BC	1.6	1.9	2.8	45	52	0.4
10. N4.6	UC	2.3	11.7	15.8	20	29	--
11. N5.1	BF	11.3	4.3	6.6	34	52	1.0
12. N4.11	RF	5.9	6.6	11.3	29	54	2.0
13. N5.3	SC	3.8	3.2	4.8	29	45	1.0
14. N6.7	BF	14.9	5.2	8.1	30	58	1.0
15. N4.7	BE	3.7	6.5	9.8	36	50	--
16. N6.4	RF	8.0	4.9	7.6	29	55	2.0
17. N5.4	UC	4.3	8.6	11.8	23	30	--
18. N6.8	BF	9.5	3.8	6.0	30	58	1.0
19. N6.3	RF	11.0	2.6	3.4	42	56	--
20. N5.2	BF	4.7	3.7	6.5	29	58	2.0
21. N6.5	BF	5.2	2.0	3.3	38	55	--
22. N4.4	BC	1.8	1.7	2.4	42	54	0.5
23. N4.2	SC	2.4	7.3	10.8	22	29	--
24. N6.2	RC	8.8	2.6	4.3	36	52	--
25. N4.1	BC	3.4	2.2	3.2	42	54	0.6

Note: The two-letter code for "Location and Type" is as follows:

Location	Type
R = rural	F = freeway
S = suburban	E = expressway
U = urban	C = conventional road
B = urban bypass	(no control of acces

Other symbols are defined as follows:

PC = passenger cars
Δh = initial cost increment
V = value of time

Economic indexes may not agree in detail, due to rounding.

12

IAY PROJECTS IN NORTH CAROLINA

duction r of:		Economic Indexes				
	Δh $(x\ 10^6)$	Transp. Cost Savings $(x\ 10^6)$		Cost of Time	Benefit/Cost Ratio	
Speed hanges		V=$1.80	V=$0.90		V=$1.80	V=$0.90
(9)	(10)	(11)	(12)	(13)	(14)	(15)
2.4	$6.6	$123.1	$109.8	$-6.52	19.6	17.6
3.4	4.1	65.9	55.7	-4.01	16.9	14.5
3.4	3.0	38.2	31.6	-3.46	13.7	11.6
2.0	1.2	14.4	12.3	-4.52	13.4	11.7
2.3	1.2	12.6	10.6	-3.82	11.5	9.8
3.4	4.7	48.9	41.5	-4.18	11.4	9.8
3.4	8.3	82.9	68.0	-3.20	11.0	9.2
3.4	2.0	15.6	12.8	-3.18	8.8	7.4
1.0	0.2	1.3	1.1	-4.07	8.4	7.3
--	0.8	5.8	3.7	-0.62	7.9	5.4
1.7	2.2	14.7	11.8	-2.77	7.8	6.5
2.4	3.3	19.2	16.0	-3.61	6.8	5.8
3.0	1.0	5.0	3.9	-2.30	5.9	4.8
3.0	6.5	30.2	24.2	-2.71	5.6	4.7
1.0	0.7	3.2	2.3	-1.38	5.5	4.2
2.4	3.5	15.4	12.2	-2.54	5.4	4.5
2.0	1.4	6.2	4.4	-1.34	5.3	4.1
3.0	3.4	12.8	9.9	-2.12	4.8	3.9
3.0	1.9	5.6	4.6	-3.45	3.9	3.4
2.4	2.7	7.5	5.6	-1.85	3.8	3.1
2.0	0.7	1.6	1.2	-1.82	3.4	2.8
1.0	0.3	0.6	0.5	-1.79	3.3	2.7
1.0	1.3	2.8	1.8	-0.83	3.1	2.4
0.2	1.6	3.1	2.0	-0.82	2.9	2.2
1.0	1.9	0.5	0.1	+0.72	1.3	1.0

savings (-29.2 million hours) and net transportation cost savings (-$33.1 million), when compared with the set obtained by a benefit/cost ratio ranking at V = 0. There can be no doubt, then, that the set obtained by a cost-of-time ranking is inferior to the set obtained by a benefit/cost ratio ranking using V = 0. Recalling the fact that the cost-of-time ranking produces the same set of projects as would be obtained by a benefit/cost ratio ranking using a -$1.77 cost of time, this conclusion appears reasonable. Negative costs of time may exist algebraically, but do not have a physical interpretation; so the use of negative costs of time for benefit/cost analyses would be inappropriate. Where the marginal cost of time is negative, zero should, therefore, be the lower limit of the values of time used in obtaining benefit/cost ratio rankings of projects.[3]

A final comment on the California projects is that there is little apparent correlation between the economic rankings and the state's actual construction priority schedule. For example, the 14 projects included in the V = $1.80 set are scheduled to be initiated in the following fiscal years: (1) FY 67, (2) FY 72, (3) FY 64, (4) FY 72, (5) FY 64, (6) FY 66, (7) FY 65, (8) FY 68, (9) FY 71, (10) FY 64, (11) FY 66, (12) FY 71, (13) FY 67, and (14) FY 64.

Actual construction priorities are of course determined by an interplay of considerations, including the date that projections of future traffic will reach the capacity of links of the existing highway network; the availability of necessary approvals of proposed freeway routes by state and local authorities; and the policy of completing links of the interstate system by 1972. Probably most of the projects in the California program are rightly considered high priority, and they are being carried out as fast as possible. Without future analysis, it should not be maintained that the District IV advance planning program ought to be or could be in a strictly economic order of priority. It would be interesting, however, to know how close the economic priority comes to the priorities that would be considered ideal by state highway officials.

North Carolina Projects

Table 12 presents summary data for the 25 North Carolina projects included in this study. The table is identical to Table 9 for the California projects, except that (a) transportation cost savings and estimated reductions in the number of signals and 10-mph speed change cycles have been added in Table 12, and (b) present worths, the rate of return, and the benefit/cost ratio at V = 0 have been dropped.

In contrast to the more complete analysis of the California projects, consideration of the North Carolina projects will be limited to a few observations stemming from the data in Table 12.

Within the three-year budget period being used for evaluation of the North Carolina projects, sufficient construction funds are available to complete all the projects in Table 12. There is not, therefore, the problem of excluding and postponing those of lower economic priority. Ideally, all projects that can possibly be initiated within a budget period should be compared, but time did not permit such a comprehensive review of the North Carolina program.

The ranking of Project No. 8 in Table 12 is of interest because the least cost alternative of the project was of a lower economic priority. A $600,000 incremental investment in Project No. 8 was proposed to provide full control of access on what would otherwise have been a conventional road. The effect of this expenditure was estimated to increase the average daily speed on the proposed bypass from 40 to 52 mph, and to eliminate two speed change cycles per mile from the road. The result was a benefit/cost ratio of 9.8 for the incremental investment, and an increase in the benefit/

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[3]As suggested by Haney (14), the set of projects selected by the cost-of-time ranking does produce the lowest average cost-of-time savings: -$1.91 per hour in the case of the data in Table 11, compared with -$1.85 per hour for the V = 0 set and -$1.83 per hour for the V = $1.80 or V = $0.90 set. However, as we have seen, this lower average cost-of-time savings would be achieved only by selection of a set of projects that is inferior to the V = 0 set both in total hours saved and in total net transportation cost savings.

cost ratio for the overall investment from R = 8.3 to R = 8.8. The project is ranked in Table 12 according to the overall 8.8 ratio of the higher cost alternative rather than the 8.3 ratio of the least cost alternative because there is no question about the economic merit of an incremental expenditure when its incremental benefit/cost ratio is higher than that of the lesser cost investment to which it is being compared.

Like the California projects, most of the North Carolina projects display rather high benefit/cost ratios at both values of time used. All but Project No. 25 would be justified even at a zero value of time if sufficient funds were available (from the + $0.72 cost of time for Project No. 25, it is evident that its benefit/cost ratio would decline below 1 if V were greater than $0.72). Also like the California projects, there appears to be little or no correlation between the priority of a project in the North Carolina advance planning program and its economic priority.

Finally, it is useful to note that the North Carolina project with the greatest sensitivity to time savings, No. 10, can be tentatively identified by inspection of the costs of time listedin Col. 13, Table 12. This is because the -$0.62 cost of time for Project No. 10 is obviously much higher than that for adjoining projects (-$3.18 and -$2.77).

Table 13

ECONOMIC RANKINGS OF NORTH CAROLINA PROJECTS BY BENEFIT/COST RATIOS

V=$1.80		V=$0.90		V=0	
Project (1)	R (2)	Project (3)	R (4)	Project (5)	R (6)
1. N6.6	19.6	1.	17.6	1.	15.6
2. N4.12	16.9	2.	14.5	2.	12.0
3. N4.9	13.7	4.	11.7	4.	9.9
4. N4.5	13.4	3.	11.6	3.	9.4
5. N4.8	11.5	5.	9.8	6.	8.2
6. N5.5	11.4	6.	9.8	5.	8.1
7. N4.10	11.0	7.	9.2	7.	7.4
8. N6.1.2	8.8	8.	7.4	9.	6.1
9. N4.3	8.4	9.	7.3	8.	6.0
10. N4.6	7.9	11.	6.5	11.	5.1
11. N5.1	7.8	12.	5.8	12.	4.8
12. N4.11	6.8	10.	5.4	14.	3.8
13. N5.3	5.9	13.	4.8	13.	3.7
14. N6.7	5.6	14.	4.7	16.	3.6
15. N4.7	5.5	16.	4.5	15.	3.0
16. N6.4	5.4	15.	4.2	18.	3.0
17. N5.4	5.3	17.	4.1	19.	2.9
18. N6.8	4.8	18.	3.9	10.	2.8
19. N6.3	3.9	19.	3.4	17.	2.8
20. N5.2	3.8	20.	3.1	20.	2.4
21. N6.5	3.4	21.	2.8	21.	2.2
22. N4.4	3.3	22.	2.7	22.	2.1
23. N4.2	3.1	23.	2.4	23.	1.7
24. N6.2	2.9	24.	2.2	24.	1.6
25. N4.1	1.3	25.	1.0	25.	0.8

Note: V = value of time; R = benefit/cost ratio. The complete project number is given in column (1); columns (3) and (5) list only the number identifying the rank order of the projects in column (1).

Table 14

SUMMARY OF DATA ON SELECTED HIGHWAY PROJECTS IN TENNESSEE

Project	Basic Project Data									Economic Indexes				
	Loc. & Type	Lgth. in Miles	ADT (x 10^3)		1980 Avg. Daily PC Speeds		Per Mile Reduction in Number of:		Δ h (x 10^6)	Transp. Cost Savings (x 10^6)		Cost of Time	Benefit/Cost Ratio	
			1966	1980	Without Project	With Project	Signals	Speed Changes		V=$1.80	V=$0.90		V=$1.80	V=$0.90
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
1. T1.12	BC	6.5	11.4	14.0	29	52	1.0	3.0	$2.4	$24.1	$19.1	$-2.53	11.3	9.1
2. T1.11	BE	2.2	10.4	11.8	27	54	2.0	3.4	0.8	7.4	5.5	-1.72	10.7	8.2
3. T1.7	BE	3.5	8.0	6.9	34	46	1.0	1.7	0.8	5.3	4.5	-4.60	7.2	6.3
4. T1.1	SC	8.2	8.8	15.5	31	38	--	1.6	1.6	9.4	6.9	-1.56	6.8	5.2
5. T2.3	SE	4.3	10.2	15.3	30	54	1.5	1.0	2.1	11.5	8.2	-1.33	6.4	4.9
6. T2.1	SE	4.1	7.3	15.6	30	58	1.5	1.0	2.2	10.9	7.7	-1.30	6.1	4.6
7. T3.1	SF	2.8	23.6	29.7	20	52	5.0	2.5	7.2	32.9	23.6	-1.38	5.5	4.2
8. T2.2	SE	5.5	7.2	14.9	30	54	1.5	1.0	3.0	12.8	8.9	-1.20	5.3	4.0
9. T4.5	SC	1.6	22.5	35.0	27	34	2.0	3.4	1.1	4.7	3.2	-0.98	5.2	3.8
10. T1.9	UF	0.9	21.8	32.2	21	52	2.0	3.4	2.2	8.7	5.8	-0.90	5.0	3.7
11. T1.13	RC	2.0	7.1	9.9	35	52	1.0	2.0	0.9	3.2	2.5	-2.62	4.6	3.8
12. T3.3	SE	3.7	8.5	13.8	38	54	--	2.0	1.3	4.5	3.4	-1.70	4.5	3.6
13. T2.10	SC	1.8	21.7	12.7	24	30	2.0	3.4	1.2	3.7	2.8	-1.66	4.2	3.3
14. T1.10	UF	0.2	14.8	23.2	21	52	4.0	2.0	0.4	1.3	0.8	-0.74	4.2	3.0
15. T2.9	UC	2.0	13.2	14.6	24	30	2.0	3.4	1.4	3.5	2.6	-1.51	3.6	2.9
16. T1.8	BE	2.8	4.5	7.3	27	58	2.0	3.4	1.9	4.3	2.9	-0.93	3.2	2.5
17. T4.2	RE	5.1	4.3	6.4	44	54	--	2.0	1.2	2.7	2.3	-3.75	3.2	2.9
18. T4.10	BC	6.3	2.1	3.1	38	50	--	2.0	1.0	2.1	1.5	-1.26	3.1	2.5
19. T2.4	RE	3.6	6.2	8.7	34	54	1.0	1.7	2.4	4.7	3.6	-1.90	2.9	2.5
20. T3.6	UC	1.0	12.9	12.2	24	30	2.0	3.4	0.7	1.2	0.8	-0.84	2.8	2.2
21. T4.3	SE	9.4	4.8	6.1	44	54	--	2.0	2.7	4.6	3.7	-3.12	2.7	2.4
22. T2.7	UC	1.3	29.1	29.1	21	27	--	1.0	1.7	2.6	1.0	+0.36	2.6	1.6
23. T2.8	SC	2.2	9.9	11.7	24	30	2.0	3.4	1.6	2.5	1.7	-0.97	2.6	2.0
24. T2.6	RC	2.3	4.7	6.6	40	54	--	2.0	0.7	1.0	0.6	-0.67	2.5	2.0
25. T1.19	RC	5.0	6.1	6.8	40	48	--	2.0	1.4	2.0	1.5	-1.65	2.5	2.1

28.	T1.5	RC	3.8	5.1	6.3	37	52	--	2.0	1.4	2.0	1.4	-1.00	2.4	2.0
29.	T1.15	RC	2.5	6.1	8.6	40	52	--	2.0	0.9	1.2	0.7	-0.60	2.4	1.9
30.	T4.1	SE	7.0	4.8	6.3	44	54	--	2.0	2.3	3.1	2.5	-2.59	2.4	2.1
31.	T1.16	RC	3.6	4.6	7.3	40	40	--	2.0	1.1	1.5	1.0	-1.12	2.3	1.9
32.	T1.4	BC	3.0	6.9	9.4	44	54	--	2.0	1.2	1.5	1.1	-1.33	2.3	1.9
33.	T4.4	UC	2.3	13.5	21.0	24	30	2.0	3.4	3.4	4.1	2.7	-0.79	2.2	1.8
34.	T4.8	RC	8.0	2.1	2.8	40	50	--	2.0	1.5	1.5	1.1	-1.81	2.0	1.8
35.	T1.2	RC	5.2	2.3	3.8	39	48	--	2.0	1.0	0.9	0.5	-0.55	1.9	1.6
36.	T3.12	RC	4.2	3.2	3.3	40	52	--	2.0	0.9	0.8	0.5	-0.77	1.9	1.6
37.	T1.18	RC	5.2	2.5	3.4	40	50	--	2.0	1.1	0.8	0.4	-0.37	1.7	1.4
38.	T1.6	RC	3.9	4.5	5.9	46	54	--	2.0	1.1	0.8	0.5	-0.72	1.7	1.4
39.	T2.11	RC	6.0	0.9	1.2	42	52	--	2.0	1.0	0.6	0.5	-3.13	1.6	1.5
40.	T3.8	RC	7.0	1.8	2.5	42	51	--	2.0	1.1	0.6	0.3	-0.24	1.6	1.3
41.	T1.3	RC	4.8	2.1	2.8	39	48	--	2.0	0.8	0.5	0.2	+0.11	1.6	1.3
42.	T3.5	UC	0.5	17.0	15.7	17	23	--	1.8	0.8	0.4	0	+0.99	1.5	0.9
43.	T3.9	RC	7.7	1.6	2.0	42	52	--	2.0	1.3	0.6	0.3	-0.28	1.4	1.2
44.	T1.17	UC	1.1	6.0	8.1	24	30	2.0	3.4	0.8	0.3	0.3	+0.94	1.3	1.0
45.	T3.7	RC	6.4	1.2	2.0	42	52	--	2.0	1.4	0.4	0.2	-0.04	1.3	1.1
46.	T3.10	RC	5.1	2.1	1.8	40	50	--	2.0	1.1	0.2	0	+0.76	1.2	1.0
47.	T4.9	RC	8.0	1.3	1.7	40	50	--	2.0	1.3	0.1	-0.2	+1.48	1.1	0.9
48.	T3.11	RC	5.5	1.5	2.0	42	50	--	2.0	1.0	0	-0.1	+1.55	1.0	0.9
49.	T1.14	RC	1.5	4.1	5.6	46	54	--	1.0	0.5	0	-0.1	+2.03	0.9	0.7
50.	T3.4	BE	2.0	1.1	1.9	27	54	2.0	3.4	1.1	-0.3	-0.3	+2.06	0.9	0.7
51.	T4.6	RC	7.5	0.4	0.6	42	50	--	2.0	1.1	-0.2	-0.3	+5.19	0.8	0.7
52.	T3.2	RE	3.5	4.1	4.8	40	52	--	2.0	2.7	-0.7	-1.1	+3.47	0.7	0.6
53.	T4.7	BC	1.7	3.4	5.5	27	38	2.0	3.4	2.6	-1.1	-1.5	+4.60	0.6	0.4
54.	T2.12	RC	3.7	0.4	0.5	40	50	--	2.0	0.7	-0.5	-0.6	+16.63	0.2	0.2

Note: The two-letter code for "Location and Type" is as follows:

Location	Type
R = rural	F = freeway
S = suburban	E = expressway
U = urban	C = conventional road (no control of access)
B = urban bypass	

Other symbols are defined as follows:

PC = passenger cars
Δh = initial cost increment
V = value of time

Economic indexes may not agree in detail, due to rounding.

The cost of time for Project No. 10 is, in fact, next to the highest in the entire project listing, and its benefit/cost ratio accordingly declines quite rapidly, as lower values of time than $1.80 are used.

Table 13 has been prepared to document further the result that the relative priority of Project No. 10 slips downward as lower values of time are used: it is 10th on the list in Table 13 at V = $1.80, 12th at V = $0.90, and 18th at V = 0. No other North Carolina project shows such a pronounced tendency to decline in priority with decreasing values of time. This fact might raise a question about the relatively high priority of Project No. 10 at V = $1.80, since it does not hold its own with other projects at lower values of time.

Tennessee Projects

Table 14 presents the same data for the Tennessee projects that were given in Table 12 for North Carolina projects.

There are many high benefit/cost ratios among the Tennessee projects at V = $1.80 or $0.90, but a larger proportion of low ratios (2 and below) than was true for the California and North Carolina projects, and several of the Tennessee ratios are below 1. This is because a higher proportion of expressways and conventional roads are included in the Tennessee set of projects than in the other two sets; such highways tend to produce smaller speed increments than do freeways. In addition, a number of the Tennessee projects are on roads with rather low ADT. For example, 14 Tennessee projects had ADT projections of less than 3,000 vehicles for 1980, compared with one project in North Carolina and none in California. Projects on roads with similarly low ADT undoubtedly exist in both California and North Carolina—for example, on the FAS system—but were not included in this study.

It should also be mentioned that at this writing the Tennessee Department of Highways is reviewing its 5-yr advance planning program, so the low-priority projects listed in Table 14 may not represent the latest thinking of the Department on its future construction plans.

Another point of interest with respect to Table 14 is that, as in North Carolina, one of the projects—No. 22—shows a particularly high sensitivity to time savings. This project has a cost of time of +$0.36 compared with costs of time for the adjoining projects of -$3.12 and -$0.97. Another project that shows relatively high sensitivity to time savings is No. 42. It is significant that both these time-sensitive projects involve the widening of conventional urban arterials. Without any reduction in the number of signals, the operating costs for traffic on these two arterials are estimated to increase slightly. The user savings for the two projects are, therefore, due entirely to savings in truck time costs, accident costs, and passenger car time costs, as summarized below:

	1966 User Savings in:			
	Operating Costs	Truck Time Costs	Accident Costs	Passenger Car Time Costs
Dollar savings (000)				
#22	-$23.1	+$14.7	+$88.0	+$256.9
#42	-$13.9	+$11.0	+$26.8	+$ 79.2
Percentage of Total 1966 Savings				
#22	- 6.8%	+ 4.4%	+ 26.1%	+ 76.3%
#42	- 13.5%	+ 10.6%	+ 26.0%	+ 76.9%

The increases in operating costs estimated above for projects No. 22 and No. 42 are due to the fact that operating costs of signals and speed change cycles increase with increasing vehicular speed (see Table A-1 in Appendix A). Closer examination of actual arterial improvements might reveal that vehicle operating costs would not be adversely affected in certain cases, as, for example, when signal synchronization is added as part of the arterial improvement.

CONCLUSIONS

The major conclusions of this study have been noted in the foregoing discussion of results; they are summarized here briefly.

1. Nearly all the projects analyzed had benefit/cost ratios of 1 or greater. Also, for a great many projects, very high benefit/cost ratios (typically from 4 to 8 and higher) and rates of return (typically from 20 to 40 percent) were obtained both at V = \$1.80 and V = \$0.90. If it were known with confidence (a) that the value of time is in the range of \$0.90 to \$1.80 per passenger car hour, and (b) that large backlogs of other state highway projects with benefit/cost ratios in excess of 1 at V = \$0.90 to V = \$1.80 do exist, these results could be interpreted as indicating the desirability of increasing highway construction budgets in order to reduce the backlog more quickly.
2. Negative costs of time tended to be the rule rather than the exception, indicating that most highway projects would be justified from a road user benefit standpoint even if the value of time were assumed to be zero. This result should raise a question about the current trend toward using higher values of time in road user benefit analysis.
3. The chronological order of projects included in the advance planning programs of two of the states bore no relation to their benefit/cost ratios. This is not intended to be a critical observation because it is recognized that many intangible factors influence project scheduling. It does, however, indicate that advance programming is not at present carried out according to economic criteria.
4. It was confirmed that the set of projects with the lowest average cost-of-time savings is obtained by ranking projects according to benefit/cost ratio criteria with V equal to the marginal cost of time. However, when the marginal cost of time was negative, the set so selected might be inferior to the set obtained at V = 0; and even the set obtained using V = 0 may then involve time-dollar tradeoffs with sets obtained using higher values of time.
5. Although the cost of time should not be used as the sole economic indicator of project desirability, the cost of time appears to have a clear and straightforward place in highway economy studies as an index of the sensitivity of benefit/cost ratios to the value of time used. Numerical or graphical supplementation of economy studies by cost-of-time data can be strongly recommended.

A final conclusion that is more a by-product than a direct result of this study is the need for greater uniformity in the conduct of highway economy studies. Sufficient standardization of methods and terminology to make the results of studies in one state comparable with the results of studies in other states would tend to broaden the usefulness and acceptability of economy studies. There seems to be no reason why greater standardization cannot be achieved. Where agreement cannot be reached on the most appropriate value of some parameter, progress might be possible by adopting one of two courses of action: (a) use of two alternative values, as was done in this study for the value of time; or (b) adoption of a standard value for purposes of comparability, but leaving individual agencies free to supplement the standard value with one of their own choosing for purposes of internal review of results.

There would be at least two major advantages to greater comparability of results of economy studies. First, with a large number of highway agencies working along common lines, investment guidelines such as break-even points for various types and levels of highway improvement would tend to be established, and these could be disseminated to and tested by other highway jurisdictions. A second advantage would be that needed areas of research on improvements in methodology could more readily be identified, and concentrated efforts could be undertaken to solve the problems. During this study, it was observed that certain areas of particular importance to the results of highway economy studies might profit from intensive research. For example, improved techniques would be desirable for estimating average daily speeds over a year or a study period, computing numbers of speed change cycles under various traffic conditions, and evaluating the effect of signalized intersections of different types on average speeds and operating costs. It would also be useful to have a better understanding of the optimum lengths of budget periods for analyzing advance highway planning programs.

A final example of the need for further research is the desirability of confirming the conclusions of this study in other states by economic analyses of entire state highway construction programs. Such analyses would of course have much greater significance if they could be carried out in a comparable manner from one state to another.

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REFERENCES

1. AASHO,. Road User Benefit Analyses for Highway Improvements, 1960.
2. Billingsley, Charles M., and Jorgenson, Dayton P., Direct Costs and Frequencies of 1958 Illinois Motor-Vehicle Accidents. Highway Res. Record, No. 12, 1963.
3. Claffey, Paul J. Characteristics of Passenger Car Travel on Toll Roads and Comparable Free Roads. Studies in Highway Engineering Economy, Highway Res. Board Bull. 306, 1961.
4. Campbell, M. Earl. Physical and Economic Rating Methods for Priority Considerations. Formulating Highway Construction Programs. Highway Res. Board Spec. Rept. 62, pp. 75-86, 1961.
5. England, Arthur C. Balancing of Physical and Economic Ratings with Other Considerations to Establish Project Priorities. Highway Res. Board Spec. Rept. 62, pp. 95-99, 1961.
6. Fleischer, Gerald A. Effect of Highway Improvement on Travel Time of Commercial Vehicles: A Twenty-Five-Year Case Study. Highway Res. Record, No. 12, 1963.
7. Grant, Eugene L. Concepts and Applications of Engineering Economy. Highway Res. Board Spec. Rept. 56, pp. 11-17, 1959.
8. Grant, Eugene L. Interest and the Rate of Return on Investments. Highway Res. Board Spec. Rept. 56, pp. 82-83, 1959.
9. Grant, Eugene L., and Oglesby, Clarkson H., Economy Studies for Highways. Studies in Highway Engineering Economy. Highway Res. Board Bull. 306, 1961.
10. Haikalis, George. Economic Analysis of Roadway Improvements. Chicago Area Transportation Study, Chicago, Ill., Dec. 1963.
11. Haikalis, George, and Campbell, E. Wilson, Quality of Traffic Service, A Basis for Highway Design Selection. Chicago Area Transportation Study, Jan. 1962.
12. Haikalis, George, and Hyman, Joseph. Economic Evaluation of Traffic Networks. Studies in Highway Engineering Economy. Highway Res. Board Bull. 306, 1961.
13. Hammond, R. J. Benefit-Cost Analysis and Water-Pollution Control. Food Res. Inst., Stanford Univ., Calif.
14. Haney, Dan G. Use of Two Concepts of the Value of Time. Highway Res. Record, No. 12, 1963.
15. Haney, Dan G. The Value of Travel Time for Passenger Cars: A Preliminary Study. Stanford Res. Inst., Menlo Park, Calif., Jan. 1963.
16. Haning, Charles R., and McFarland, William F., Value of Time Saved to Commercial Motor Vehicles through Use of Improved Highways. Texas Transportation Inst., Texas A and M Univ., Bull. No. 23, Sept. 1963.
17. Hirshliefer, J. On the Theory of Optimal Investment Decision. In the Management of Corporate Capital. The Free Press of Glencoe, Illinois, pp. 205-228, 1959.
18. Kent, Malcolm F. Fuel and Time Consumption Rates for Trucks in Freight Service. Motor Vehicle Time and Fuel Consumption. Highway Res. Board Bull. 276, 1960.

19. Krutilla, John V., and Eckstein, Otto. Multiple Purpose River Development, Baltimore, Maryland, The Johns Hopkins Press, 1958.
20. Lorie, J. H., and Savage, L. J., Three Problems in Rationing Capital. In the Management of Corporate Capital. The Free Press of Glencoe, Illinois, pp. 56-66, 1959.
21. Malo, A. F., Mika, H. S., and Walbridge, V. P., Traffic Behavior on an Urban Expressway. Highway Res. Board Bull. 235, 1960.
22. McKean, Roland N. Efficiency in Government through Systems Analysis. New York, N. Y., John Wiley and Sons, 1958.
23. Norman, O. K. Research Needed to Keep Pace with Changing Traffic Trends. Traffic Quarterly, Vol. 12, No. 3, July 1958.
24. Solomon, Ezra. The Arithmetic of Capital-Budgeting Decisions. In the Management of Corporate Capital, The Free Press of Glencoe, Illinois, pp. 74-79, 1959.
25. Stanford Res. Inst. Economics of Asphalt and Concrete for Highway Construction, April 1961.
26. State of Tennessee. Manual of Procedure for a Planned Construction Program for the Tennessee State Highway System. Dept. of Highways, June 1961.
27. U. S. Department of Commerce. Highway Capacity Manual. Washington, D. C., U. S. Bureau of Public Roads, 1950.
28. Winfrey, Robley. Concepts and Applications of Engineering Economy in the Highway Field. Highway Res. Board Spec. Rept. 56, pp. 19-23, 1959.
29. Winfrey, Robley. Highway Economics. In Highway Engineering Handbook. McGraw-Hill, 1960.
30. Winfrey, Robley. Motor Vehicle Running Costs for Highway Economy Studies, Arlington, Virginia, Robley Winfrey, Nov. 1963.
31. Granum, James O., and Burnes, Clinton. Advance Programming Methods for State Highway Systems. Highway Needs and Programming Priorities. Highway Res. Board Bull. 249, 1960.
32. McCarthy, James F. Economic Cost of Traffic Accidents in Relation to the Vehicle. Economic Cost of Traffic Accidents. Highway Res. Board Bull. 263, 1960.
33. Bierman, Harold, Jr., and Schmidt, Seymour. The Capital Budgeting Decision. The Macmillan Co., 1960.
34. Mohring, Herbert. The Nature and Measurement of Highway Benefits: An Analytical Framework. Northwestern Univ. Transportation Center, June 1960.

Appendix A

DERIVATION OF INCREMENTAL PRESENT WORTHS

Compilation of Project Data

Data were first sought from state highway agencies on the physical characteristics of each proposed new highway section and of the routes being improved or replaced; on the number and location of stop signals; total traffic and truck percentages in present and projected traffic on the routes; projected 1980 average daily speeds; and the estimated costs associated with proposed improvements. In cases where some of the necessary information was not available, independent estimates of the missing data were made from a study of the route characteristics. The bases for the most important of the independent estimates that had to be made are discussed below.

Estimates of 1966, 1980, and 1990 ADT

The initial year of state traffic projections ranged from 1960 to 1962 for the various projects studied, and the terminal year varied from 1975 to 1985. Usually, only estimates of ADT in the initial and terminal year were given, with no prediction of probable interim ADT values. For consistency, straight-line interpolations and extrapolations of the state projections were therefore made to obtain ADT estimates in 1966, 1980, and 1990 for all projects. For some routes, a constant annual percentage increase of traffic might have been more reasonable, but no basis existed for identifying such exceptions. Also, the slow absolute increase of traffic in the initial years of a new highway improvement that would be implied by a constant percentage traffic increase does not conform to frequent observations of rapid initial traffic growth on an improved highway facility.

Estimates of ADT were sought both for traffic shifted to the improved highway facility and for traffic remaining on existing parallel roads. Benefits from relief of congestion on existing parallel roads are often substantial, typically resulting in increases on the order of 5 to 10 mph in average daily speed. Benefits to cross-traffic from the elimination of intersections at grade would also have been desirable to consider, but for most projects, no complete network-type of traffic study was available to furnish the necessary ADT and speed estimates on cross-traffic.

Use of 1980 Average Daily Speed

Vehicular speeds decline as traffic increases on a highway, so that the average speed on a facility where traffic is increasing year by year should ideally be computed for each year of the study period. However, the average daily speeds which are of interest in economy studies will be less sensitive to a given traffic increment than the average speeds in the most congested hours of the day; and for most types of highway, there is a fairly wide range of traffic over which average daily speed varies only slightly. Furthermore, present methods of estimating average daily speeds are not so exact that a year-by-year calculation of weighted speeds for a single "25-year average speed" is likely to be worth the additional refinement obtained over selecting a typical traffic year for computation of a single representative annual speed. The speed for a single year has the added advantage of some concrete relation to reality, so that it can be said--if all predictions are correct--that "by year n, the speed on route B will be x miles per hour." Two or three years could also be chosen, scattered throughout the study period, if a larger sample is desired.

For the cost-of-time study, average daily speed in the single year 1980 was selected as a simplification to represent the average speed for the period 1966-90. The year 1980 was chosen because the speed-reducing effects of congestion should begin to be felt by that year on highways where congestion is an important factor in speed reduction.

Estimating Average Daily Speed

Since most road user benefits are directly related to increases in the freedom of traffic movement as measured by the average speed of motor vehicles, it was thought to be of importance to use the best techniques available for estimating the average daily speed in 1980. Review of a number of speed-estimating techniques used by state highway agencies and metropolitan area transportation studies led to the adoption of the following combination of assumptions and procedures:

1. A group of average daily passenger car speed-volume curves was sought that would be in reasonable relation to each other for three major types of roads: freeways, undivided rural highways, and urban arterial streets (the usual status of state

surface highways passing through cities and towns). Development of the curves required consulting a number of different sources and the use of some judgment where existing data were inadequate.

As a beginning, the curve developed by the Chicago Transportation Study (CATS) for a full 8-lane urban freeway (11) was plotted, and similar curves were drawn for 6-lane and 4-lane urban freeways (assuming reduced capacities in proportion to the reduced number of lanes). The average daily speed for each of these curves is constant at 52 mph out to about 25 percent of maximum daily capacity, at which point a decrease with added traffic density begins. From current speed checks of interstate highways in California, Mississippi, and North Carolina, similar curves were estimated for rural freeways, with average daily speeds beginning at 58 mph and decreasing as the ADT reaches 20 percent of maximum daily capacity.

For rural 2-lane and 4-lane roads without access control, hourly speed-volume curves developed by O. K. Normann (23) were adjusted to daily speeds by the rough factors suggested in the AASHO Redbook (1, p. 89) and smoothed slightly to place the maximum average daily speed on high-grade rural roads at 54 mph, for consistency with current state rural speed checks.

For urban arterials, free-moving traffic between signals was estimated from current speed checks in the San Francisco Bay area, which indicate that traffic moves at or slightly below the posted speed limits. Starting with the curve for a 4-lane arterial used by CATS (11), speeds and capacities as volume increased were estimated for 22-foot, 42-foot, and 64-foot street widths at two different speed limits using the "Urban Facility of Movement" analysis procedure developed by the Automotive Safety Foundation for the Tennessee Highway Department (26, pp. A-14 through A-41). The slowing effect of stop signals was computed at low volumes for the urban arterials on the basis of average delays of 10.8 seconds per car.*

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* Such an average could, for example, involve one-half of the automobiles being stopped by each signal, for an average of 21.6 seconds delay per vehicle stopped, including roughly 6-8 seconds standing delay and 14-16 seconds for acceleration and deceleration. Some stopped vehicles would of course be delayed a longer and some a shorter period than this, depending on when they arrived during the signal cycle and

The speed-volume curves resulting from the foregoing analysis are shown in Figure A-1 for level, tangent highways with surfaces in good condition. Some of the uses and limitations of these curves are discussed in succeeding paragraphs.

2. It will be noted that the speed-volume curves in Figure A-1 reflect higher maximum daily road capacities than those ordinarily assumed. One reason that lower capacities are often assumed is that design-hour traffic is usually taken as a single specified percentage of ADT--such as 12.5 percent for rural areas and 10 percent or 11 percent for urban areas. However, as traffic increases on a route, it is common for the ratio of peak-hour traffic to ADT to decrease, owing to greater utilization of the road during off-peak hours; and under extremely heavy traffic situations it is not uncommon to encounter 30th highest hours that are only 7 percent to 8 percent of ADT. The effect is to increase the daily traffic capacity beyond that which would be implied by a higher design-hour percentage. The curves in Figure A-1 reflect this progressively decreasing design-hour percentage; for example, the 200,000 daily capacity of the 8-lane freeway could be achieved if the design hour is 7 percent of ADT, with a 60-40 directional split of traffic and 2,100 vehicles per lane in the direction of heaviest flow.

3. The curves shown in Figure A-1 are only illustrative of high quality level tangent roads of 12-foot lane width, 6-foot or wider shoulders, and with no stop signals (except on the urban arterials where lane widths of about 10.5 feet, no shoulders, and indicated signal frequencies are assumed). Speeds estimated for individual project routes also took into account available data on posted speed limits, substandard lane or shoulder widths, grades, impaired passing sight distance (for 2-lane rural roads), and stop signals or signs. The use of 1980 for the average daily speed computation also necessitated assumptions as to future roadside development and additional signalization where projected traffic growth was rapid or the route went through densely populated areas with no provisions for access control.

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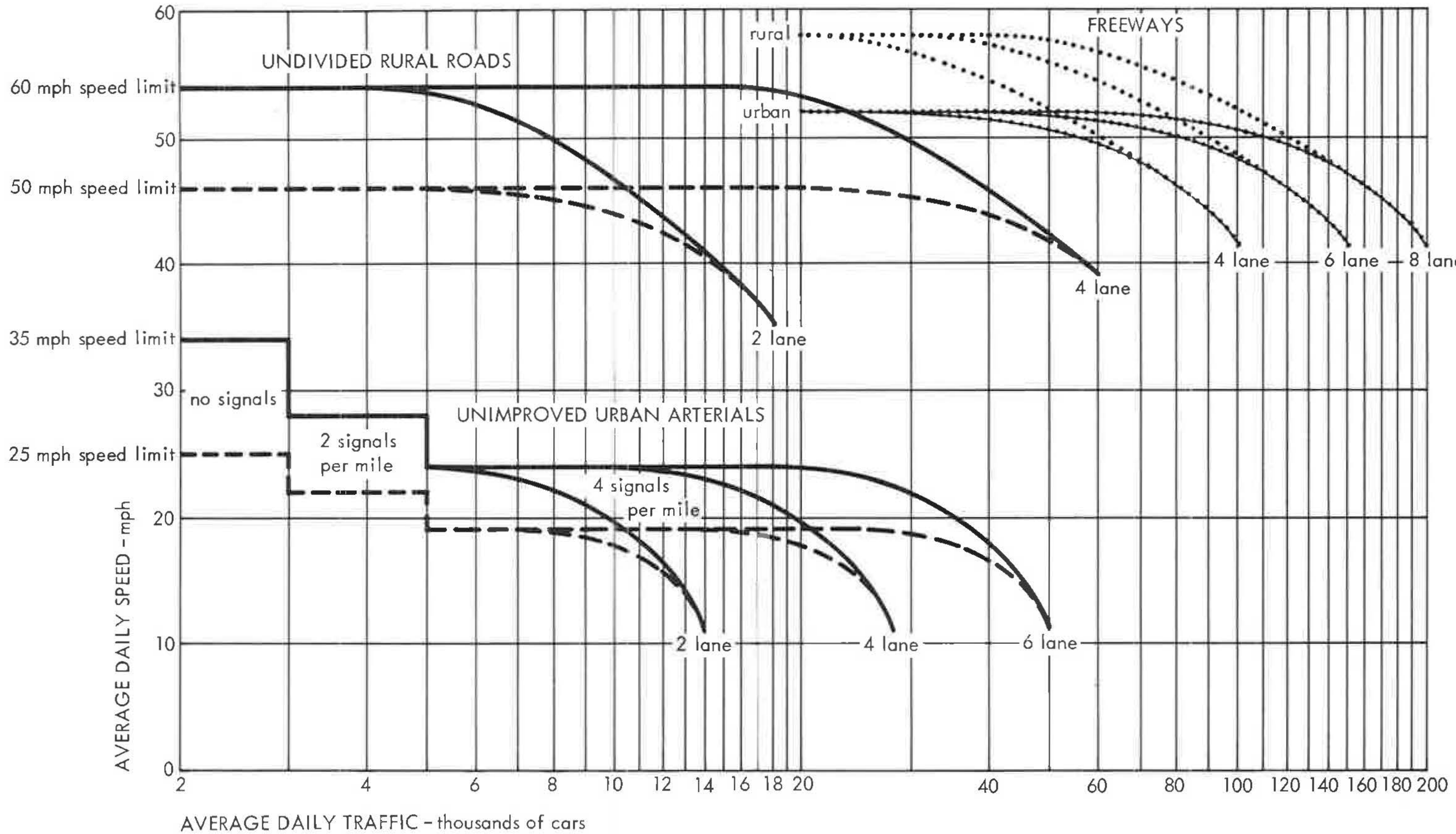
how congested the intersection was. Also, the indicated average would not necessarily be applicable to special conditions such as synchronized or traffic-actuated signals.



SOURCES: See text.

Figure A-1. Typical passenger car speed-volume relationships for level tangent highways.

4. Data from state speed checks indicated lower average speeds for trucks than for passenger cars by about 5 percent to 25 percent, even on level roads and highways. This observation is supported by the practice of most states in prescribing lower speed limits for trucks than for automobiles. Average daily truck speeds on the level were accordingly taken as 10 percent lower than the passenger car speeds shown in Figure A-1. The effect of trucks on vehicle volumes for speed-volume relationships was reflected by using the following truck/passenger car equivalents for obtaining traffic volume in passenger car equivalents:*

Terrain	Average Truck Speed (mph)	Truck Equivalents in Passenger Cars
Flat to light rolling	40-up	2
Rolling	30-35	4
Mountainous	25	8
Mountainous	20	13
Mountainous	15	20

5. Figure A-1 was developed in the absence of the anticipated revision of the Highway Capacity Manual, and will have to be reassessed in relation to the revised manual when it is available.

Maintenance and Resurfacing Costs

In cases where specific maintenance cost estimates by state highway agencies were available for a route, those estimates were used for this study. For the majority of projects, however, average maintenance costs per lane mile had to be used. The averages were developed from a sample of maintenance costs for the states under study, for which the greatest number of cases fell between $600 and $1,400 annually per lane mile.

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* Sources: Reference 23, page 343, and Reference 26, page A-30.

These costs covered patching and other surface repair, landscaping, weeding, traffic striping, sign upkeep, and signal operation. Resurfacing, snow removal, sanding, and overhead costs were excluded.

Since samples of maintenance costs for divided highways tended to be higher by about $200 per lane mile than for undivided highways, owing chiefly to added landscaping requirements for the divided highways, estimates of $900 per lane mile for undivided highways and $1,100 per lane mile for divided highways were taken as representative maintenance costs for existing roads. For new construction, however, the estimates of $900 and $1,100 were taken as the end-of-period annual maintenance cost, and an equivalent annual cost was computed at 5 percent interest under the assumption that maintenance costs would begin at 64 percent of end-of-period costs, climb at a constant annual gradient to 100 percent in 10 years, and remain constant at 100 percent thereafter. The result, rounded off, was equivalent to a reduction of 11 percent or some $100 from the $900 and $1,100 average maintenance cost estimate for existing roads.* The final estimates are summarized below.

	Undivided Roads	Divided Roads
Existing routes	$900	$1,100
New construction	$800	$1,000

These estimates are admittedly rough, but appear close to present estimating practices of some states. For example, the estimate of $1,000 per lane mile for new construction of divided roads is consistent with estimates of $4-5,000 per mile that are currently used by several states for future annual maintenance costs of 4-lane interstate highways.

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* The average gradient of maintenance costs used here was inferred from trends observed in Reference 25. As an indication of the relatively low sensitivity of maintenance costs to the gradient assumed--an initial maintenance cost of 44 percent, climbing to 100 percent in 15 years, would be equivalent at 6 percent interest to a reduction of 25 percent instead of 11 percent from the annual end-of-period maintenance costs. Such a gradient would have resulted in annual maintenance estimates for new construction of $700 and $800 instead of $800 and $1,000, respectively, for undivided and divided roads.

Resurfacing of new roads was assumed to be required only after 25 years, involving no costs within the study period. Even if a resurfacing was required a few years sooner, the present worth of the expenditure at 6 percent interest would be small enough to ignore. For example, an expenditure of $10,000 per lane mile for resurfacing after 20 years would be equivalent, at 6 percent interest, to only $1,370 per lane mile today, or $107 per year for 25 years on an equivalent annual basis.* This is less than the possible margin of error in annual maintenance costs alone. Resurfacing at intervals of less than 20 years was considered unlikely. Design criteria developed during the recent AASHO road tests make possible the construction of either concrete or asphalt road surfaces that should last 25 years before resurfacing is needed, assuming that truck traffic has been correctly forecast and that a high grade of asphalt is available (which may not always hold for Western States).

Maintenance and resurfacing costs on an existing road present a somewhat special problem. For example, where the existing route is to be bypassed and left intact by a proposed improvement, maintenance and resurfacing costs for the existing route are of course common to both the existing route and the proposed improvement, and may be ignored. In cases where part or all of the existing route is to be abandoned or taken over by a proposed improvement, however, maintenance costs and the cost of any necessary resurfacing of the superseded part of the existing route should be included as part of the cost of the existing or "do-nothing" alternative, thereby representing added savings attributable to the improvement. However, a test of the sensitivity of the sample project in Annex B to varying assumptions about resurfacing of the existing road indicated that the matter was not significant in relation to the overall economy study.**

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* Because a resurfacing after 20 years is so near the end of the 25-year study period, a salvage value at the end of the study period equal to 75 percent of the original cost of the resurfacing was assumed for this computation.

** See sensitivity checks 5 and 6 in Table B-5, Appendix B. Even avoidance of resurfacing the entire superseded road in year one of the study period did not add appreciably to the favorability of the economic indexes for the new highway.

Calculation of 1966 User Costs and Savings

The year 1966 was used as a base for calculating annual vehicle miles traveled on the existing route and on any proposed new routes. The combination of annual vehicle miles, average daily 1980 speeds, and stop-signal information enabled the calculation of total 1966 user costs for all alternatives and, through comparison of the alternative routes, the relative user savings for one alternative versus another. A description of the assumptions and cost factors underlying these calculations follows.

Operating Costs

The operating costs for this study are based on a new series developed by Robley Winfrey (30) which excludes taxes from the price of gasoline in order to avoid double counting. Gasoline taxes are "transfer payments" to state highway agencies, and should properly be counted as transportation costs for economy study purposes only at the time they are expended by the agency for construction, maintenance, and other costs. Other innovations in Winfrey's operating cost series include the graduation of maintenance and depreciation costs by speed; the inclusion of compatible tables for incremental time and operating cost requirements of stops and speed change cycles; and the analysis of operating costs for several types of trucks.

It is well known that automobile operating costs at constant speeds tend to rise after a speed of 30 or 35 mph, and hence that the use of constant-speed operating cost factors does not provide for valid computation of savings in operating costs due to increases in average speed through the elimination of stops and speed change cycles. For this study, the constant-speed operating cost factor served as a point of departure; to it were added cost factors for the estimated differences between alternative routes in the number of stops and speed change cycles per mile.* The operating cost for signals was based on the assumption

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* The number of 10 mph speed change cycles were estimated as a function of type of road and volume of traffic from data for trucks given in Reference 18, Figure 9. The operating cost of a 10 mph speed change cycle (from Winfrey's tables) is quite substantial, amounting to between 80 and 100 percent of the average increase in operating costs caused by stopping at signals (as computed in Table A-1). Ideally, it would also be desirable to include the incremental operating costs of curves, but while Winfrey's tables provide the necessary cost factors, data on curves were not uniformly available for the projects included in this study.

of 10.8 seconds delay for vehicles traveling at speeds of 15 to 34 mph between signals; 12.6 seconds for speeds of 35 to 39 mph; and 14.4 seconds for speeds of 40 to 50 mph. If 50 percent of vehicles are stopped by each signal, these assumptions allow for the acceleration and deceleration times computed by Winfrey, and for from 6 to 8 seconds of average standing delay per vehicle stopped. A standing delay of 5.4 seconds per vehicle at stop signs was assumed. The resulting passenger car operating costs for signals and for stops are summarized in Table A-1.

In order to develop composite operating cost factors for trucks, the percentage distribution of the three types of trucks in Winfrey's tables was assumed as follows:

40 percent - 12,000-lb gross weight single unit truck
30 percent - 40,000-lb gross weight 2-S2, gasoline powered
30 percent - 50,000-lb gross weight 3-S2, diesel powered

Table A-1
PASSENGER CAR OPERATING COSTS
DUE TO SIGNALS AND STOPS

Approach Speed (mph)	Cents per Vehicle Mile for Indicated Number of Signals per Mile					
	1	2	3	4	5	6
50	1.28	2.56	3.85			
40	0.81	1.62	2.44	3.25	4.06	
35	0.63	1.26	1.90	2.53	3.16	3.79
30	0.49	0.98	1.47	1.96	2.45	2.94
25	0.37	0.74	1.11	1.48	1.86	2.23
20	0.27	0.55	0.82	1.09	1.36	1.64
15	0.19	0.38	0.57	0.76	0.95	1.14
	Cents per Vehicle Mile for Indicated Number of Stop Signs per Mile					
50	2.53	5.06	7.60			
40	1.59	3.19	4.78	6.37	7.96	
35	1.24	2.48	3.72	4.96	6.20	7.45
30	0.95	1.91	2.86	3.81	4.76	5.72
25	0.71	1.43	2.14	2.85	3.56	4.28
20	0.51	1.02	1.54	2.05	2.56	3.07
15	0.34	0.69	1.03	1.37	1.72	2.06

These percentages assume a greater proportion of truck combination vehicles on the highways than the AASHO Redbook recommendation of 70 percent single unit trucks, 29 percent truck combinations, and 1 percent buses (1, p. 29). However, a 40-30-30 distribution appears to be much more representative of the present truck distribution by type on FAP and interstate highways, based on traffic and speed surveys in California, North Carolina, and Mississippi conducted since 1960. Seldom in these surveys did truck combinations fall below 50 percent of the total truck count,* and frequently combinations would run 70 percent or more of total trucks observed on through truck routes. A 40-60 division between single unit trucks and truck combinations therefore seemed a reasonable approximation of the average (ideally, separate counts should be available and estimated for the two types on routes being planned for construction). The use of equal percentages for a 40,000-lb gasoline vehicle and a 50,000-lb diesel vehicle is fairly arbitrary, but operating costs for the two types of vehicles are not so different that serious errors are likely to arise from this assumption.

Truck operating costs on grades were computed from Winfrey's tables for a single "average" truck, using the same assumption of a 40-30-30 distribution of truck types as described above. However, the operating costs of truck stops and of 10 mph truck speed change cycles (based on the same average truck) turned out to be relatively constant multiples of similar passenger car operating costs over the range of 25 to 60 mph. These multiples were computed as 7.0 × passenger car operating costs for stops, and 7.5 × passenger car operating costs for 10 mph speed change cycles.

A summary of constant-speed passenger car and truck operating cost factors for high quality, level, tangent highways is included in Table A-2. Passenger car operating cost factors are also shown in relation to total passenger car cost factors in Figure A-2.

Truck Time Costs

The value of truck time savings cannot be reckoned with as much reliability as the operating cost savings of motor vehicles, owing largely to uncertainties about the timing of the monetary value of the truck time savings. As demonstrated by Gerald Fleischer at the 1963 Highway Research Board meetings (6), the realization of dollar savings by truck operators may be delayed several years beyond the incidence of the time savings themselves. This delay has been recognized in a recent study by Charles Haning and William McFarland of the Texas Transportation Institute (16), in which it is concluded that the average incremental value of time for a composite commercial freight vehicle ranges from $3.16 to $4.11 per

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* Excluding all lightweight 4-tired vehicles such as panels and pickups.

hour, depending on the degree to which the potential value of the time savings can actually be realized. The lower end of this range, or \$3.16 per hour, is recommended by the authors where a single value is needed; this has been rounded to \$3.20 per hour for the present study. Known assumptions of state highway agencies as to the value of truck time range from \$1.80 to \$4.80 an hour, and \$3.20 is well within this range.

As a rough check on the reliability of \$3.20 per hour as a conversion factor for truck time savings, it is useful to look at drivers' wages, which account for roughly 90 percent of the potential savings calculated by Haning and McFarland. The union scale for truck drivers' wages currently ranges approximately between \$3 and \$4 per hour when payment is on an hourly basis. Payment of line haul drivers on a mileage basis is the most common practice, at a current rate of about 10¢ per mile; at the over-all average truck speed of 40 mph, which is used as a "rule of thumb" by truck freight companies, 10¢ per mile is equivalent to \$4.00 per hour.

As Fleischer observed, union contracts commonly include a clause limiting reductions in wages owing to construction of shorter routes. At present, wage reductions are limited to about one-sixth of the reduced mileage per year. Thus the effect of any mileage savings on truck drivers' wages is spread out over a six-year period. Also, when wages are computed on a mileage rather than an hourly basis, time savings alone may not be convertible into cost savings until enough time is saved to eliminate a discrete block of expenses such as an overnight stop. In relation to realizable savings in truck drivers' wages, then, a figure of \$3.20 an hour does not seem an unreasonable average. There may of course be demonstrable cases where a certain highway improvement is just enough to enable a large, discrete block of cost savings due to truck time savings, but over a large number of projects, such savings should average out with cases where little if any time savings can be translated into cost savings.

Accident Costs

The direct and measurable costs of highway accidents are the subject of frequent debate and speculation, and in spite of the difficulties inherent in defining the costs of human injury and death, a number of states use accident cost factors which assign some dollar value to the known increase in safety of freeways compared with conventional roads. However, in only one case known to this writer has a series of accident costs been developed that is graduated over a wide range of vehicular speeds. That case is the series used by the Chicago Area Transportation Study to predict total accident costs in the Chicago area under varying traffic plans (12). The CATS series indicates an inverse relation between accident costs and speed, ranging, for example, from 1.8¢/mile at 20 mph to 0.2¢/mile at 58 mph. The series was developed on the basis of observed accident frequencies at different speeds, and the accident cost predictions originally made for the Chicago area on the basis of the CATS series have recently been corroborated through an accident cost study conducted by the Urban Research Section of the Illinois Division of Highways (10, p. 32).

While the CATS accident cost series would not necessarily apply to analyses of individual roads with unusually high or low accident rates, it was thought to be representative enough of the average case to use for passenger cars in this study. Because evidence from the Illinois accident study (2, p. 75), as well as the earlier Massachusetts accident study (32, p. 24), indicates that average truck accident costs per vehicle mile are only about one-half of the figures for passenger cars, the CATS accident costs have been divided by two for trucks. The series of accident costs at selected speeds is listed in Table A-2.

Value of Passenger Car Time

Because of uncertainties about the proper value of passenger car time, the two widely separated values of $0.90/hr and $1.80/hr were used throughout this study, and as a third value, the value of time was set equal to either (a) the marginal cost of time for the construction budget from which a given project was financed, or (b) to zero, if the marginal cost of time was negative. The value of $1.80 per hour approximates the midpoint of the range of values used in many states at the present time ($1.55 to $2.00 per hour). No effort was made to convert improvements in the "comfort and convenience" of highway users to dollar benefits.

Summary of Road User Cost Factors

Table A-2 summarizes the various components of total user costs employed for this study, and Table A-3 gives savings in user costs as a result of selected increases in constant speed of passenger cars. Figure A-2 is a graphic illustration of the data in Table A-2. Note in Figure A-2 that decreases in total costs due to further speed increases become quite small as the lower speed in question reaches the range of 30 to 40 mph. However, in the frequent cases when the lower speed in question is for traffic experiencing more stops and speed change cycles per mile than the higher speed traffic with which it is being compared, the added user savings from eliminating some of the stops and speed change cycles may be substantial, and Figure A-2 would be misleading. (See, for example, the textual comments on Table B-3 of the sample project analysis in Appendix B.)

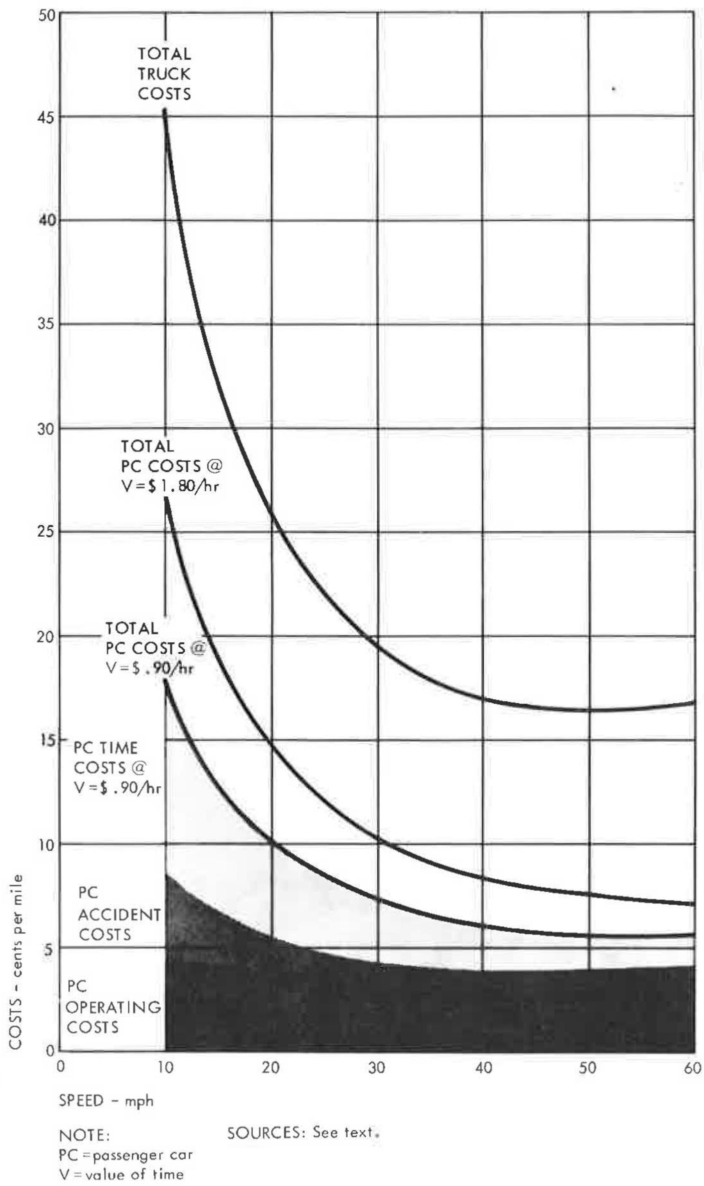

Figure A-2. Road user cost factors for level tangent highways.

Table A-2

SUMMARY OF ROAD USER COST FACTORS
(Cents per Mile, on Level, Tangent Highways)

Speed (mph)	Operating Costs		Truck Time @ $3.20/hr	Accidents		PC Time		Total PC		Total Trucks
	PC	Trucks		PC	Trucks	V=$1.80	V=$0.90	V=$1.80	V=$0.90	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
60	3.94	11.84	5.33	0.18	0.09	3.00	1.50	7.12	5.62	17.26
59	3.91	11.63	5.42	0.19	0.10	3.05	1.52	7.15	5.62	17.15
58	3.87	11.42	5.52	0.20	0.10	3.10	1.55	7.17	5.62	17.04
57	3.83	11.22	5.61	0.21	0.11	3.16	1.58	7.20	5.62	16.94
56	3.80	11.02	5.71	0.22	0.11	3.21	1.61	7.23	5.63	16.84
55	3.77	10.82	5.82	0.23	0.12	3.27	1.64	7.27	5.64	16.76
54	3.75	10.64	5.93	0.24	0.12	3.33	1.67	7.32	5.66	16.69
53	3.72	10.47	6.04	0.25	0.13	3.40	1.70	7.37	5.67	16.64
52	3.70	10.30	6.15	0.26	0.13	3.46	1.73	7.42	5.69	16.58
51	3.67	10.14	6.27	0.27	0.14	3.53	1.76	7.47	5.70	16.55
50	3.65	9.99	6.40	0.28	0.14	3.60	1.80	7.53	5.73	16.53
49	3.64	9.86	6.53	0.29	0.15	3.67	1.84	7.60	5.77	16.54
48	3.62	9.72	6.67	0.30	0.15	3.75	1.88	7.67	5.80	16.54
47	3.60	9.60	6.81	0.31	0.16	3.83	1.91	7.74	5.82	16.57
46	3.58	9.48	6.96	0.32	0.16	3.91	1.96	7.81	5.86	16.60
45	3.56	9.36	7.11	0.33	0.17	4.00	2.00	7.89	5.89	16.64
44	3.55	9.25	7.27	0.34	0.17	4.09	2.05	7.98	5.94	16.69
43	3.53	9.15	7.44	0.35	0.18	4.19	2.09	8.07	5.97	16.77
42	3.52	9.06	7.62	0.36	0.18	4.29	2.15	8.17	6.03	16.86
41	3.51	8.97	7.80	0.37	0.19	4.39	2.20	8.27	6.08	16.96

39	3.50	8.81	8.21	0.41	0.21	4.62	2.31	8.53	6.22	17.23
38	3.49	8.74	8.42	0.44	0.22	4.74	2.37	8.67	6.30	17.38
37	3.48	8.67	8.65	0.47	0.24	4.86	2.43	8.81	6.38	17.56
36	3.48	8.60	8.89	0.51	0.26	5.00	2.50	8.99	6.49	17.75
35	3.48	8.54	9.14	0.55	0.28	5.14	2.57	9.17	6.60	17.96
34	3.48	8.50	9.41	0.60	0.30	5.29	2.65	9.37	6.73	18.21
33	3.48	8.47	9.70	0.65	0.33	5.45	2.73	9.58	6.86	18.50
32	3.48	8.43	10.00	0.70	0.35	5.63	2.81	9.81	6.99	18.78
31	3.49	8.41	10.32	0.75	0.38	5.81	2.90	10.05	7.14	19.11
30	3.49	8.38	10.67	0.80	0.40	6.00	3.00	10.29	7.29	19.45
29	3.50	8.37	11.03	0.87	0.44	6.21	3.10	10.58	7.47	19.84
28	3.51	8.37	11.43	0.94	0.47	6.43	3.21	10.88	7.66	20.27
27	3.53	8.38	11.85	1.01	0.51	6.67	3.34	11.21	7.88	20.74
26	3.54	8.39	12.31	1.08	0.54	6.92	3.46	11.54	8.08	21.24
25	3.56	8.41	12.80	1.15	0.58	7.20	3.60	11.91	8.31	21.79
24	3.59	8.45	13.33	1.27	0.64	7.50	3.75	12.36	8.61	22.42
23	3.61	8.50	13.91	1.40	0.70	7.83	3.91	12.84	8.92	23.11
22	3.64	8.56	14.55	1.50	0.75	8.18	4.09	13.32	9.23	23.86
21	3.67	8.64	15.24	1.65	0.83	8.57	4.29	13.89	9.61	24.71
20	3.71	8.72	16.00	1.80	0.90	9.00	4.50	14.51	10.01	25.62
19	3.75	8.84	16.84	1.95	0.98	9.47	4.74	15.17	10.44	26.66
18	3.80	8.97	17.78	2.10	1.05	10.00	5.00	15.90	10.90	27.80
17	3.85	9.12	18.82	2.30	1.15	10.59	5.30	16.74	11.45	29.09
16	3.91	9.31	20.00	2.50	1.25	11.25	5.63	17.66	12.04	30.56
15	3.97	9.49	21.33	2.70	1.35	12.00	6.00	18.67	12.67	32.17
14	4.06	9.64	22.86	2.90	1.45	12.86	6.43	19.82	13.39	33.95
13	4.14	9.79	24.62	3.15	1.58	13.85	6.92	21.14	14.21	35.99
12	4.25	10.12	26.67	3.40	1.70	15.00	7.50	22.65	15.15	38.49
11	4.37	10.65	29.09	3.80	1.90	16.36	8.18	24.53	16.35	41.64
10	4.49	11.17	32.00	4.25	2.13	18.00	9.00	26.74	17.74	45.30

PC = Passenger cars.
V = Value of time.

Table A-3

ILLUSTRATIVE SAVINGS FROM INCREASES IN CONSTANT SPEED OF PASSENGER CARS
(Level Tangent Highways)

Speed (mph)		Savings, in Cents per Vehicle Mile, due to:						Savings as Percent of Original Total Costs	
				PC Time		Total			
Original	New	Operating Costs	Accident Costs	V=$1.80	V=$0.90	V=$1.80	V=$0.90	V=$1.80	V=$0.90
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
20	25	0.15	0.65	1.80	0.90	2.60	1.70	17.9%	17.0%
20	30	.22	1.00	3.00	1.50	4.22	2.72	29.1	27.2
20	35	.23	1.25	3.86	1.93	5.34	3.41	36.8	34.1
20	40	.21	1.42	4.50	2.25	6.13	3.88	42.2	38.8
20	45	.15	1.47	5.00	2.50	6.62	4.12	45.6	41.2
20	50	.06	1.52	5.40	2.70	6.98	4.28	48.1	42.8
25	30	.07	0.35	1.20	0.60	1.62	1.02	13.6	12.3
25	35	.08	0.60	2.06	1.03	2.74	1.71	23.0	20.6
25	40	.06	0.77	2.70	1.35	3.53	2.18	29.6	26.2
25	45	0	0.82	3.20	1.60	4.02	2.42	33.8	29.1
25	50	-.09	0.87	3.60	1.80	4.38	2.58	36.8	31.0
30	35	.01	0.25	0.86	0.43	1.12	0.69	10.9	9.5
30	40	-.01	0.42	1.50	0.75	1.91	1.16	18.6	15.9
30	45	-.07	0.47	2.00	1.00	2.40	1.40	23.3	19.2
30	50	-0.16	0.52	2.40	1.20	2.76	1.56	26.8	21.4

PC = Passenger car.
V = Value of time.

Expansion of 1966 User Savings to a 25-Year Series, and Calculation of Incremental Present Worths

The expansion of 1966 user savings to the full 25 years of the 1966-90 study period was carried out using an equal annual increment of savings. The annual increment or gradient of savings was taken as proportional to the annual increment of ADT, since ADT enters into each component of user savings and may even be factored out if desired. The annual user savings gradient was obtained through multiplying 1966 user savings by the following gradient:

$$G = \frac{\text{annual ADT increment}}{\text{1966 ADT}}$$

A 25-year series of user savings was derived by adding multiples of the annual user savings gradient to successive years of the 1966-90 study period (beginning with $\times 1$ in 1967, $\times 2$ in 1968, etc.). The results were combined with estimates of initial investment and annual maintenance costs, and were utilized in a computer program for the derivation of present worths at 6 percent interest.

The next few paragraphs will describe the reasons for selecting a 6-percent interest rate and 25-year study period.

Choice of Interest Rate

The choice of an interest rate for use in economy studies for government investments has been approached from a number of directions, and a wide variety of rates may be defended, depending upon the approach taken. One promising approach for highway investments is to use an interest rate that is approximately representative of the opportunity cost of capital--that is, the rate that could be earned by funds if left in private hands rather than being collected by the government in the form of taxes, sometimes also referred to as the market rate of interest. There appear to be three major premises behind basing interest rates on the opportunity cost of capital: (1) nearly all resources are limited, including capital; (2) the future value to the investor of a limited resource for its most productive alternative use--i.e., its opportunity cost--is a proper estimate of its cost for the purposes under study; and (3) market prices are in most instances the best available measure of value, in this case the value of capital, regarding money simply as another productive resource.

It should be noted that no assumptions as to the risks of highway investments are involved in the premises underlying the opportunity cost of capital. Risk can be brought into an economic analysis in more explicit ways, such as by the use of a range of probable values instead of a single average estimate when a decision might be affected by possible shifts in an uncertain estimate. The length of the study period is another device for introducing considerations of risk: the greater the uncertainties about distant forecasts of benefits and costs associated with a particular type of investment, the shorter should be the study period.

There is a practical difficulty in attempting to find the most representative market rate of interest by averaging the hundreds of fluctuating rates of return that are typical of our society; to mention a few, high-grade bonds may pay only 3 or 4 percent; savings and loan associations currently pay between 4.5 and 5 percent; advance payments by home owners on their mortgages represent completely risk-free investments of about 6 percent; and many other rates of return ordinarily run up to the 10-15 percent range, such as the rates on automobile or personal loans and the return on business investments. Nevertheless, there is a surprising amount of agreement among persons who have recently suggested interest rates that are approximately representative of the opportunity cost of capital. For example, Robley Winfrey in the Highway Engineering Handbook has suggested a range of from 5 to 8 percent, chiefly on the basis of opportunity cost but including some component "to allow for the risk involved and to bring the banker's straight interest rate up to the public's desired rate of return" (29). Professor Eugene Grant has suggested a 7 percent rate for analysis of highway investments (8), partly on the grounds that it would be close to the opportunity cost of capital and partly because it is a typical minimum attractive rate of return used by public utilities in their own economy studies (and therefore includes some allowance for risk?).

A final example is the approach taken by John Krutilla and Otto Eckstein in their 1958 book Multiple Purpose River Development (19). In Chapter IV of this book, the authors review in great depth the probable average rate of return that would be achieved by funds released to the public in a tax cut. Their conclusion is that in average years--that is, excluding times of severe recession or inflation--the average rate of return achieved would very probably lie between 5 and 7 percent, and most probably between 5 and 6 percent.

For this study, an interest rate of 6 percent has been used as a representative opportunity cost of highway investment funds. If private investments can be made that will, on the average, return at least 6 percent to road users, the necessity for a lower rate to justify highway investments should be considered as an argument for reducing gasoline taxes, unless there are persuasive intangible reasons for building roads that return less than their investment costs.

Possible Use of Marginal Rate of Return

An alternative to setting the discount rate on the basis of the market rate has been suggested by Roland McKean, who notes in his excellent discussion of the problem of time streams and investment criteria that the method of choosing the discount rate should depend (1) in part on whether or not capital is rationed (i.e., the investment budget has been fixed at higher levels) and (2) in part on whether or not the resale of the investment is contemplated (22, pp. 74-127). For the case most similar to highway investments, that of capital rationing with resale not contemplated, McKean recommends use of the marginal rate of return* (that is, "the yield that could be earned in the next-best opportunities open to the investor") for discounting all projects. In effect, then, McKean's criterion for setting the interest rate is still the opportunity cost of capital, but he looks to alternative investments within an organization rather than to the market place for determining the opportunity cost.

Space does not permit a detailed consideration of McKean's recommendation here, but it is perhaps sufficient to note that rate-of-return solutions imply that the benefits anticipated from an investment will be reinvested (if more than two time periods are involved) at the same rate of return. In contrast, benefits from highway investments accrue to road users, and presumably any reinvestment of road user benefits would have to be at the market rate, or about 6 percent, rather than at the yield that could be earned "in the next-best opportunities" open to the highway department. McKean's recommendation is, therefore, inappropriate to highway economy studies, because as he remarks (p. 85):

> "If net receipts can be reinvested at the marginal internal rate, its use as the discount rate gives the right answers. If net receipts cannot in fact be reinvested at that rate . . . then that internal rate is not the marginal rate of return and is no more relevant than the internal rate of return on Saturn."

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* McKean uses the term "internal rate of return" synonomously with the use of "rate of return" in this paper.

It must be mentioned that the conclusion McKean reaches with regard to beneficiaries of water-resource projects is that the receipts will be reinvested at the government's marginal rate of return for water-resource projects because ". . . the government will probably continue to collect taxes on the general public equal to (or greater than) these hypothetical receipts and invest them in water-resource programs" (22, p. 116). If McKean's argument is valid, it would seem correct to extend it to similar types of government investments, including highway programs.

However, the author feels that such an argument confuses a possible coincidental result with a necessary consequence. To support McKean's position it is not only necessary to argue that tax receipts for water-resource and highway projects will somehow be maintained at an approximate equilibrium with the public benefits from past projects in those areas; it is also essential to show that the relationship is a causal and not a coincidental one.

As an example of a causal relationship, one might attempt to demonstrate that an interruption of highway investment in the first few years of a certain 25-year period would necessarily result in a reduction of highway investment during later years because of the missing benefits from the projects that were not built in the early years. On the contrary, of course, exactly the opposite effect was observed after the interruption of highway construction during World War II, when the large backlog of delayed projects helped to create pressure for accelerated highway construction in the years following the war.

From such historical examples as this, it appears more reasonable to conclude that the levels of government investment for water-resource and highway programs are and will continue to be based in large part on demonstrable needs, rather than solely on the receipts accruing to beneficiaries from government outlays for previous water-resource and highway projects.

Examples of Varying the Reinvestment Rate

Since the position is taken in this paper that reinvestment of road user benefits should be assumed at the market rate of interest rather than at some higher marginal rate of return, it is important to show that a distinction of some consequence to highway economy studies is involved. Examples are given below of two investments that it is desired to rank in order of relative priority by the simplest and most easily interpretable method.

It will be assumed that the investments are not mutually exclusive (that is, both of them could be undertaken if desired).

Example 1. For a 25-year series of constant annual net benefits of $15.47 from a $100 initial investment, the conventional rate of return would be 15 percent, and the end-of-period value of the cash benefit stream (assuming reinvestment of receipts at 15 percent) would be $3,290. However, if benefits are assumed to be reinvested at a market rate of 6 percent instead of the 15 percent rate implied by rate-of-return computations, the end-of-period cash value of the benefits would be only $850, which is equivalent to an "effective" rate of return of 8.9 percent on the original $100 investment. These results are summarized below:

Investment No. 1	Benefits	End-of-Period Cash Value with Reinvestment at: 6%	15%	Effective Rate of Return with Reinvestment at: 6%	15%
$100	$15.47/year for 25 years	$850	$3,290	8.9%	15%

Example 2. For investments with a conventional 15 percent rate of return where benefits tend to fall later in the study period, the effective return at a 6 percent reinvestment rate would be higher than for investments with constant benefits. Thus, an initial investment of $100 that produced constant annual benefits of $10.00 per year for 25 years plus an annual gradient of $.93 beginning in year 2 would have the following characteristics:

Investment No. 2	Benefits	End-of-Period Cash Value with Reinvestment at: 6%	15%	Effective Rate of Return with Reinvestment at: 6%	15%
$100	$10/year + $.93 gradient	$1,010	$3,290	9.7%	15%

Two of the accepted methods of determining the relative desirability of the two foregoing investments are (1) comparing the more costly investment's incremental rate of return with some minimum attractive rate of return, and (2) comparing the more costly investment's incremental benefit/cost ratio with a benefit/cost ratio of 1. If the minimum attractive rate of return used in the rate-of-return method is the same as the interest rate used in computing present worths for the benefit/cost ratio method, then the two methods should give identical results. This, in fact, is the case for the two examples given if it is recognized that the rate-of-return solution in this case requires year-by-year subtraction of the cash benefits of the one investment from the other. For example, the incremental benefits in selected years of the study period would be computed as follows:

	Actual Cash Value of Benefits in Selected Years			
	Year 1	Year 6	Year 7	Year 25
1. Investment No. 1	$15.47	$15.47	$15.47	$15.47
2. Less: Investment No. 2	10.00	14.65	15.58	32.32
3. Incremental investments and benefits	+5.47	+.82	-.11	-16.85

The correct interpretation of line 3 in the above tabulation is to regard the incremental deficiency of cash benefits accrued by the second investment during years 1-6 of the study period as a series of net investments, which return an incremental excess of cash benefits during years 7-25 of the study period ($16.85 in year 25, for example). The conventional rate of return on the resulting series of incremental investments and benefits (line 3 of the foregoing tabulation) is 15 percent; since this rate of return exceeds the minimum attractive rate of return, Investment No. 2 would be selected as most attractive.

The incremental benefit/cost ratio solution is obtained by taking the present worth of incremental benefits of Investment No. 2 over Investment No. 1 at 6 percent interest (which turns out to be +$38) divided by the incremental investment required in Investment No. 2 (which is $0). The result, $+\infty$, is greater than 1, and Investment No. 2 is therefore favored.

The discussion of the two investment examples so far has been in terms of conventional methods of comparing their relative desirability. It is evident that both conventional methods give consistent answers, when correctly applied. The objective with which this discussion was begun, however, was to rank the two proposals "by the simplest and most easily interpretable method." The reason for seeking a simpler method than either of those just illustrated is that in ranking a complete highway program, each project must be compared with each other project in order to rank the whole set. Such a process becomes extremely burdensome for a large number of projects; for example, 25 to 54 projects had to be ranked in each of the three states visited for this study, and the hundreds of project intercomparisons necessary would have been quite time consuming. Even if a computer program could be devised to solve the problem more quickly, the question is still relevant: Why do it the hard way, even on a computer, if an easier way exists?

The "easier way" of ranking that is proposed in this paper is according to a project's benefit/cost ratio, as illustrated in the text under Calculation of Economic Indexes; and it is possible to show by the two investment examples given above that a ranking by the conventional rate of return may produce results that are inconsistent with a ranking by benefit/cost ratios. Specifically, comparison of the two investments by their conventional rates of return would be indeterminate, since both streams of investment would return 15 percent on the original investment; however, the following comparison of benefit/cost ratios readily and correctly identifies the Investment No. 2 as the one that would rank highest:

	Present Worth of Benefits at 6% Interest	Initial Cost	Benefit/ Cost Ratio
Investment No. 1	\$198	\$100	1.98
Investment No. 2	236	100	2.36

A slight change in the data for Investment No. 1, sufficient to cause an increase of 0.1 percent in its conventional rate of return, would cause it to be definitely selected by a rate-of-return ranking without altering the benefit/cost ratio decision in favor of Investment No. 2. That a case such as this is not purely theoretical can be seen in the section of the text California Projects, where rate-of-return and benefit/cost ratio rankings result in selection of different sets of projects.

The reason for the inconsistency of results between rankings by conventional rates of return and by benefit/cost ratios lies in the implicit assumption of the conventional rate-of-return computation that interim benefits can be and are reinvested at the rate of return of the particular project. When this assumption is removed, and when reinvestment of benefits at the market rate of 6 percent is recognized, the effective rates of returns of 8.9 percent for Investment No. 1 and 9.7 percent for the second investment permit identification of Investment No. 2 as the more desirable one. There seems to be no reason why a project's effective rate of return would not be as good a ranking index as the benefit/cost ratio, but the conventional rate of return--defined as that rate that makes the present worth of future benefits equal to initial costs--appears inappropriate.* What may be even worse, use of the conventional rate of return for highway projects is obviously misleading if in fact a reinvestment rate of about 6 percent is correct, because the effective rate of return is less than two-thirds the magnitude of the conventional rate of return in the examples given. For a 20 percent conventional rate of return, the effective rate of return would be only about 10 percent or one-half the conventional rate, indicating that the error increases as the difference between the conventional rate of return and the actual reinvestment rate widens.

So far, the discussion has been limited to the problem of ranking non-mutually-exclusive investments. For ranking a series of mutually-exclusive investments using benefit/cost ratios, an iterative procedure that involves the use of incremental benefit/cost ratios on incremental investments is necessary. The suggested technique is explained in the main body of this paper under <u>Ranking of Competing Projects</u>, and was used in ranking the California and North Carolina sets of projects. The iterative procedure recommended does not affect the validity of the foregoing arguments against use of the conventional rate of return as a ranking index.

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* It is felt by some that the rate-of-return index is more readily interpretable than other indexes; from this point of view, the use of an effective rate-of-return method would have merit.

Length of Study Period

Selection of a limited time period for economy studies is based on a number of considerations, chief among which is the limitation of human foresight in predicting the consequences of an investment (29, pp. 3-11 and 3-12). The potential useful life of an investment from an engineering point of view is largely irrelevant, especially since interim expenditures for maintenance and restoration of any perishable components of the investment (such as road surface) can readily be included in the analysis, and the remaining value of durable components at the end of the study period can be reflected in salvage value if necessary. Also, a discount rate of 6 percent conveniently reduces the sensitivity of the present worth of future net income streams to increases in the length of the study period beyond 25 or 30 years (9, p. 34). These facts led to the adoption of a single study period, in contrast to the AASHO Redbook practice of using different lifetimes for pavement, major structures, right of way, etc.

There is a natural basis for shorter study periods for highway investments than for certain types of resource development projects. For example, the river flow characteristics that establish the size and life of a dam are predictable with much greater certainty than the highway traffic growth that establishes the necessary capacity of a highway. It is unlikely that the average annual runoff of a river will increase by 200 or 300 percent from predicted levels, or fail consistently by 50 percent to achieve an average level based on many years of records; yet such possibilities must be admitted in the case of traffic flow on a new highway. A 25- or 30-year target may therefore be far enough ahead for planning highway construction, whereas it would be foolish in most cases to build a dam to last for only 25 or 30 years. The use of a relatively short analysis period has been advocated by Winfrey (28, p. 22), and Professors Grant and Oglesby have questioned the use of a study period different from the length of the traffic projection being used (9, p. 33).

A 25-year study period was adopted for this study from the foregoing considerations because it appears to represent the average limit of current highway traffic projection practice. Some state highway agencies make only 20-year traffic projections; some take an initial 25-year target and hold the terminal date fixed for 5 years, so that the length of the actual projection varies between 20 and 25 years; and others use 25- or 30-year projections.

Actually, it is extremely difficult to ascribe any absolute theoretical superiority to a 25-year highway study period as compared with, say, a 30-year period. However, a practical consideration that gave some weight to the choice of a 25-year study period in this case was the inability of some highways planned for the traffic of 1980 or 1985 to handle an extrapolation of traffic increases out to 1995. At the end of 25 years, if current state traffic predictions are correct and highway use is still increasing, it will be necessary to review the need for expanding or supplementing a significant proportion of the highways being built today. The common practice of buying extra right of way for additional future freeway lanes at the time a new freeway is first laid out reflects an awareness of this problem. It is obviously inappropriate to continue the computation of road user "benefits" past the point where traffic on a facility will have again slowed down to a crawl due to congestion, and where a substantial new investment of some sort--undeterminable at the present time--will be needed for relief. Also, the risk is not totally absent that a certain number of highways will fail to develop their predicted traffic load, as in the case of one toll highway that is even now failing to pay its way.

Salvage Value

No terminal highway salvage values have been assumed in present worth computations for this study, in agreement with prevailing practices for public works investments that are not sold or transferred to other uses at the end of the study period. It is true that highway improvements are engineered on the assumption that they will continue to be useful even after 25 years, but as already indicated, a 25-year study period was chosen as a hedge to allow for the probability and risk of human error in forecasting the future. Once having thus allowed for imperfect foresight, it appears inconsistent (from the economic rather than the engineering point of view) to qualify the hedge by ascribing a terminal value to the highway on the assumption of continued use. It would be more straightforward simply to use a longer study period in the first place. In any case, an economy study period of 25 years at 6 percent interest renders equivalent present worth relatively insensitive to assumptions about salvage value (9, p. 35).

Present Worth Formulas

The present worths of increments, designated by "Δ" (delta), have been used throughout this study for ease of computation of the economic indexes discussed in the text under Methodology. In place of the computer program used for the study, it would have been possible to derive the values of Δh, Δm, Δu, and Δt by the definitions and formulas listed below.

Initial Cost Increment

Δh = initial right-of-way and construction cost increment covering costs of right of way; final design; excavation, grading, subbase and base preparation; paving; structures; signals and signs; and landscaping. A 10 percent increase was made in initial costs (except right of way) for engineering and contingencies, when state construction estimates did not include the costs of design and supervision or an allowance for contingencies.

Maintenance Cost Increment

Δm = pwf (difference between alternatives in annual road maintenance costs)

where:

Δm = present worth of difference between alternatives in annual road maintenance costs

pwf = present worth factor, to convert a uniform series of future payments to an equivalent present worth at interest rate i (6 percent in this case)

User Savings in Operating, Truck Time, and Accident Costs

$\Delta u = \left(\text{pwf} + G\left[\text{gpwf}\right]\right)$ (1966 user savings in operating, truck time, and accident costs)

where:

Δu = present worth of user savings in operating, truck time, and accident costs

G = gradient

= annual ADT increment ÷ 1966 ADT

gpwf = gradient series present worth factor, to convert a uniform annual gradient series to an equivalent present worth

Passenger Car Time Savings

$\Delta t = \left(\text{pwf} + G\left[\text{gpwf}\right]\right)$ (hours of passenger car time saved in 1966)

where:

Δt = present worth of passenger car time savings, in hours

The definition of Δh, Δu, and Δt in terms of present worths instead of equivalent annual costs is arbitrary; equivalent annual costs would produce exactly the same benefit/cost ratios and costs of time, so long as the interest rate used for obtaining annual costs was the same rate used for obtaining present worths.

The discounting of future time savings to find Δt requires some explanation, since time savings involve the physical measurement of hours, and the discounting procedure is normally applied only to economic values. The necessity of discounting time savings arises from mathematical factors that are best considered separately for the benefit/cost ratio and cost-of-time formulas, as follows:

1. In the formula for the benefit/cost ratio that is used in this paper, passenger car time savings are expressed as an independent variable, in hours. Normally, the total value in dollars of the passenger car time savings would be discounted, but discounting the time savings first is mathematically equivalent, as illustrated by the following equality:

$$F(Vt_1 - Vt_0) = VF(t_1 - t_0) = V\Delta t$$

where

F = discount factor

$\quad$ = pwf + G(gpwf)

V = value of passenger car time, in dollars per hour

t_1 = 1966 passenger car time on proposed improvement

t_0 = 1966 passenger car time on existing roads

Δt = present worth of passenger car time savings, in hours

2. The present worth of passenger car time savings (Δt) becomes separated from its multiplicand (V) in the process of deriving the cost-of-time formula, by solving for the V at which $\Delta h = \Delta u + V\Delta t - \Delta m$. The resulting cost-of-time formula, or

$$C = \frac{\Delta h + \Delta m - \Delta u}{\Delta t}$$

results in a value for C that is mathematically comparable with V; if the time savings were not discounted, C would be understated (i.e., a smaller or "more desirable" value would be obtained) and would no longer be comparable to V. Thus, a failure to discount time savings in the cost-of-time formula would result in placing too great a weight on the value of distant time savings compared with near-future time savings.

Appendix B

SAMPLE PROJECT ANALYSIS

Background

As an illustrative project, we have approximated the actual data from a proposed new 10.6 mile section of an interstate route which bypasses two small towns in a rapidly growing rural area about 20 miles from a metropolitan center. The known and estimated data on the existing route (designated as Alternative 0; i.e., zero) and the proposed freeway route (designated as Alternative 1) are summarized in Table B-1. Alternative 1 has been divided for analysis purposes into a 4-lane and 6-lane section, which differ significantly from each other in their traffic estimates.

Speed Estimate for Alternative A

All data in Table B-1 were obtained from state highway records or estimated by methods described in Appendix A, except those of the average daily speed for Alternative 0; the latter requires special explanation.

The density of surrounding and roadside development anticipated for the existing 2-lane road by 1980 is such that it would have essentially the characteristics of an urban arterial, with increased numbers of crossroads and stop signals. An estimate of two signals per mile by 1980 seems conservative. The average 1980 ADT estimate of 41,800 (in passenger car equivalents) could not, of course, be accommodated by any 2-lane road, even without traffic signals, crossroads, or impaired passing sight distance. Preferably, then, Alternative 1 should not be compared with the existing 2-lane road, but with the minimum improvement necessary to accommodate the anticipated traffic. The speed-volume curves in Figure A-1 of Appendix A, however, indicate that a daily traffic load of 41,800 passenger car equivalents will cause serious congestion and speed reduction even on a 4-lane rural road without stop signals. Furthermore, designation of the Alternative 1 route as part of the interstate system has already assured that a freeway will be built through the area, so that it is hypothetical to postulate a conventional road as a substitute.

The only remaining assumption that warrants consideration in connection with speed selection for Alternative 1 is that the traffic growth predicted for the area would probably not take place without construction of the planned freeway. If it is further assumed that the U.S. rate of population and economic growth are given factors, the traffic growth predicted for the planned freeway would tend to shift to more

Table B-1

BASIC DATA ON ILLUSTRATIVE PROJECT

Item	Alternative 0 2-Lane	Alternative 1		Alternative 0 if 1 is Built
		4-Lane	6-Lane	
Length (miles)	10.6	7.6	3.0	10.6
Lane width (feet)	12	12	12	12
Shoulder width (feet)	8	5 & 10	5 & 10	8
Inadequate passing sight distance	60%	0%	0%	60%
ADT 1961	8,700	6,300	9,200	1,600
1966	16,300	11,800	17,200	3,000
1980	38,000	27,400	40,000	7,000
1990	53,400	38,600	56,300	9,800
Annual increment	+1,540	+1,115	+1,625	+283
Truck percentage (of ADT)	10%	10%	10%	10%
ADT in PC equivalents* 1980	41,800	30,100	44,000	7,700
1990	58,700	42,500	61,900	10,800
Signals/mile, 1980	2	0	0	1
Speed changes/mile, 1980**	3.4	0	0	2.0
Average daily PC speed, 1980	27 mph	57 mph	57 mph	35 mph
Initial cost (right of way plus construction)	--	$20,000,000		--

Note: PC = passenger cars.

* Computed from ADT by setting one truck equivalent to two passenger cars.

** Estimated number of 10 mph speed change cycles per mile in excess of number anticipated on a freeway (<u>18</u>, Figure 9).

readily accessible areas if it were not constructed.* The question then should be: How fast, on the average, could drivers be expected to move on heavily traveled non-freeway main roads in suburban areas of comparable

* These assumptions could lead down several other interesting paths. It might, for example, be profitable to speculate on the optimum areas in which to encourage growth by freeway construction, or on alternative regional and national transportation schemes that take all modes of transportation into account. Such speculation is beyond the scope of this paper; for the highway under study, it must be assumed that the broad outlines of the interstate system have already been determined, presumably after sufficient attention to other possible solutions to the over-all transportation problem.

desirability, by 1980? While the data do not exist for answering this question precisely, it has been assumed that the type of 1980 travel just described would take place at an average speed of 27 mph, on roads containing two stop signals per mile and on which drivers average 3.4 speed change cycles per mile in excess of speed change cycles during freeway travel. The assumed number of signals and speed change cycles would cause a speed decrease of some 7 mph from an average running speed of 34 mph. In effect, a 27 mph average speed estimate might therefore imply that the normal traffic growth of the country could be absorbed on existing or moderately improved surface roads, without freeways, and still leave traffic traveling at an average daily running speed of 34 mph through developed areas. This does not seem too high a speed estimate, and test runs made by Paul Claffey in 1959 provide the following rough corroboration that the average daily passenger car speed through developed areas is already in the 25 to 30 mph range (3, p. 9):

	2 Lanes	4 Lanes
Average over-all speed of study vehicle on primary routes:		
Outside downtown areas of large cities	24.9 mph	31.1 mph
Through small towns	29.6	27.2

Finally, the use of a 35 mph average daily speed estimate in 1980 for the existing route of the sample project (Alternative 0) after construction of the freeway section (Alternative 1) needs explanation. The anticipated increase from 27 to 35 mph is due primarily to removal of over 80 percent of the traffic from the existing route. The traffic remaining on the existing route would travel at an average daily running speed of 45 mph, based on the curves in Figure A-1 for a tangent, 2-lane rural road without signals. Further adjustment of -6.8 mph for the one signal per mile anticipated on the rural route if the freeway is built, -2.2 mph for impaired passing sight distance, and -1 mph for two 10-mph speed change cycles per mile in excess of freeway travel brings the average daily speed down a total of 10 mph, to 35 mph.

Explanation of Table B-2

Through use of the cost factors and formulas described in Appendix A, the basic data on the sample project from Table B-1 were translated into the various economic indexes of project desirability summarized in Table B-2. An explanation of the columnar headings in Table B-2 follows:

Table B-2

COMPARISON OF ECONOMIC DATA FOR ALTERNATIVE METHODS OF ANALYZING SAMPLE PROJECT

Method	Millions					C	R	Rate of Return
	Δh	Δm	Δu	Δt	S			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1 Original version	\$20.0	\$ --	\$26.2	25.9	52.7	\$-0.24	3.64	12.6%
2 Shift zero year to 1965	20.0	--	35.5	34.3	77.2	-0.45	4.86	17.8
3 Use 6% interest and 25-year study period	20.0	--	22.2	21.5	40.8	-0.10	3.04	18.6
4 Include road maintenance costs	20.0	0.61	22.2	21.5	40.2	-0.07	3.01	18.4
5 Revise user cost factors and add costs for stops and speed change cycles	20.0	0.61	65.8	21.6	83.9	-2.10	5.20	28.9
6 Include benefits to traffic on existing rural roads	20.0	0.61	68.4	23.6	90.2	-2.02	5.51	30.2

Note: Δh = initial cost increment
Δm, Δu, and Δt = incremental present worths of maintenance costs; user savings in operating, truck time, and accident costs; and time savings
S = transportation cost savings
C = cost of time
R = benefit/cost ratio

Column (1), Method. Six methods of economic interpretation of the data supplied in Table 1 are presented. The first of these is a composite of typical features from engineering economy methods used by many states. Methods 2-6 illustrate the step-by-step modification of Method 1 to the basic method used throughout this study. In each of Methods 1-6, Alternative 1 of the sample project is being compared with Alternative 0, the existing route. Interpretation of the six methods is given under Discussion of Results.

Columns (2) through (5): Δh, Δm, Δu, Δt. These are the incremental present worths defined at the end of Appendix A: initial highway cost, incremental maintenance costs; user savings in operating, truck time, and accident costs; and passenger car time savings (in hours).

Columns (6) through (9): Transportation Cost Savings (S), Cost of Time (C), Benefit/Cost Ratio (R), and Rate of Return. These are the economic indexes for the sample project, computed from the values of Δh, Δm, Δu, and Δt in columns (2) through (5), together with the value of time (V) taken as equal to \$1.80 per hour.

Discussion of Results

Method 1. This method is based on a 20-year study period with a zero year of 1960, a 0 percent interest rate, the exclusion of road maintenance costs, and other features that will become evident in the comparisons with Methods 2 through 6. Based on the given assumptions, Alternative 1 would result in transportation cost savings of $52.7 million; a cost of time of -$.24; a benefit/cost ratio of 3.64; and a rate of return of 12.6 percent. The negative cost of time indicates that total highway costs ($\Delta h + \Delta m$) are more than offset by the present worth of user savings (Δu) exclusive of the value of passenger car time savings.

Method 2. By shifting year zero of the study period five years forward to 1965, sizable increases in user benefits and changes in economic indexes are obtained: $24.5 million increase in transportation cost savings; $.21 decrease in the cost of time; 1.2 increase in the benefit/cost ratio; and 5.2 percentage points increase in the rate of return. This shift of the zero year is realistic, since the project was originally studied over the period 1960-80 but actually was not included in the state's highway construction budget until fiscal years 1963-64 and 1965-66.

Method 3. Use of a 6 percent interest rate to reflect the opportunity cost of capital and a 25-year study period results in decreases of S and R to below the values of Method 1, and an increase in C above the value of Method 1. A small increase (0.8 percentage points) is caused in the sample project's rate of return by the use of a 25-year instead of a 20-year study period. The rate of return is not, of course, affected by the interest rate used for obtaining the present worths in columns (2) through (5).

Method 4. The maintenance costs of the new freeway are estimated at $1,000 per lane mile, as explained in Appendix A. It is evident from the slight relative changes in S, C, R, and the rate of return that sizable errors in the maintenance estimate would still not appreciably affect the results of the analysis. The reason for this low sensitivity of the sample project to maintenance costs is that Δm (the present worth of maintenance costs, or $610,000) is only 3 percent of Δh (initial costs of the project, or $20,000,000), and the inclusion of Δm therefore causes a decrease of only .03 in the benefit/cost ratio. Maintenance costs were nevertheless estimated for all projects included in this study in spite of the low sensitivity of the sample project analysis to maintenance costs, because for some projects or incremental investments Δm could constitute a larger and perhaps significant percentage of Δh.

Method 5. In contrast to Methods 1 through 4 (which employ the road user cost factors prescribed in the highway economy study manual of the state where the sample project is located), Method 5 employs the cost factors described in Appendix A of this paper. Briefly, the operating costs are from a new series developed and published by Winfrey; truck time costs are set at $3.20 per hour, following a recent study by the Texas A & M Transportation Institute; and accident costs are adapted from a series developed by the Chicago Area Transportation Study. Table B-3 compares the two sets of cost factors at the speeds estimated for the sample project. The increase in savings per mile caused by use of the new cost factors is shown in column (7) of Table B-3.

The relatively large increases between Methods 4 and 5 in operating cost savings are due to the high operating costs of the stops and speed change cycles included in Method 5. For the two signals and 3.4 speed change cycles per mile estimated for Alternative 1, these costs were computed as follows:

	Cost Factors per Mile	
	For Two Signals	For 3.4 Speed Change Cycles
Passenger cars	1.3¢	1.7¢
Trucks	7.0	10.3

One significant result of the increased operating cost savings summarized in Table B-3 is a considerable decrease (from 64 percent in Method 4 to 37 percent in Method 5) in the percentage of total user savings that are due to the savings in cost of passenger car time.

Method 6. Method 6 differs from Method 5 only by the inclusion of benefits to the traffic expected to be left on the existing 2-lane rural road after route 1 is constructed. (As noted in Table B-1, it is anticipated that average daily speeds on the existing road will be increased by 10 miles per hour, and that one less stop signal and 1.4 fewer speed change cycles per mile will be necessary.) This seemingly small change adds $6.3 million or about 7.5 percent to the transportation cost savings of Alternative 1, resulting in a change of +.31 in the benefit/cost ratio. The change in the benefit/cost ratio between Methods 5 and 6 can therefore be interpreted as an increase in the present worth of benefits, which is equivalent to about one-third of the initial investment. We mention this for reference in the sensitivity checks which

Table B-3

COMPARISON OF SAVINGS ACHIEVED BY USING OLD AND NEW ROAD USER COST FACTORS

	Speeds, on Alternative: 0	1
Passenger cars	27 mph	57 mph
Trucks	24 mph	51 mph

	Cost Factors per Mile for Methods 1-4			Cost Factors per Mile for Method 5			Increased Savings by Use of New Cost Factors (6) - (3)
	0	1	Saving	0	1	Saving	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Operating costs							
Passenger cars	4.7¢	4.6¢	+0.1¢	6.4¢	3.8¢	+2.6¢	+2.5¢
Trucks	18.0	16.0	+2.0	25.7	10.1	+15.6	+13.6
Truck time costs*	20.0	9.4	+10.6	13.3	6.3	+7.0	-3.6
Accident costs							
Passenger cars	1.0	0.5	+0.5	1.0	0.2	+0.8	+0.3
Trucks	--	--	--	0.6	0.1	+0.5	+0.5
Totals**							
Passenger cars	5.7	5.1	+0.6	7.4	4.0	+3.4	+2.8
Trucks	38.0	25.4	+12.6	39.6	16.5	+23.1	+10.5

* Truck time = $4.80/hr for methods 1-4, $3.20/hr for method 5.

** Excluding the value of passenger car time, which is assumed to be $1.80/hr for all six methods.

follow, because one method of interpreting the sensitivity of an economic analysis to various changes is by the relative change in the benefit/cost ratio.

Table B-4 illustrates the basic worksheet computations involved in obtaining 1966 user savings for Method 6. There are four sections to the form, numbered I-IV, and the basic data flow is: vehicle miles (Section I, column 4) × cost factors (Section II) = total user costs (Section III). Section IV gives the user savings obtained on each alternative compared with all other alternatives. The format illustrated in Table B-4 would also, if necessary, handle two alternative routes in addition to 1, designated as "2" and "3."

As Table B-4 is now set up, the sum of columns (5), (6), and (7) in Section IV gives 1966 user savings in operating, truck time, and accident costs, and column (8) gives the value of 1966 passenger car time savings in thousands of dollars. To find 1966 passenger car time savings in hours, divide the amount in column (8) of Section IV by the value of time. (Note that it is possible to identify in Section IV the proportion of total user savings due to each of the four user cost factors. If this refinement is not desired, the computations involved in obtaining total user savings could be reduced slightly by combining columns (5), (6), and (7) in Sections II, III, and IV.)

Table B-4
EXAMPLE OF USER SAVINGS
COMPUTATION SHEET

Section I Project Data				Section II Cost Factors (¢/mile)				
Alter- native	Speed (mph)	Vehicle Type	1966 Veh. Mi. (10^6)	Operating Costs	Truck Time	Accident Costs	Passenger Car Time	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	
Traffic left on existing roads								
0	27	P. cars	56.9	6.41	--	1.01	6.67	
	24	Trucks	6.3	25.68	13.33	0.64	--	
1	35	P. cars	10.5	6.04	--	0.55	5.14	
	32	Trucks	1.2	23.75	10.00	0.35	--	
2		P. cars			--			
		Trucks					--	
3		P. cars			--			
		Trucks					--	
+ Traffic shifted to new facilities								
1	57	P. cars	46.5	3.83	--	0.21	3.16	
	51	Trucks	5.2	10.14	6.27	0.14	--	
2		P. cars			--			
		Trucks					--	
3		P. cars			--			
		Trucks					--	
Section III Total 1966 User Costs								
			0	5,265	840	615	3,795	
($\$ \times 10^3$)			1	3,227	446	167	2,009	
			2					
			3					1966 Total
Section IV 1966 User Savings								(9)
			0-1	2,038	394	448	1,796	4,666
			0-2					
($\$ \times 10^3$)			0-3					
			1-2					
			1-3					
			2-3					

Table B-5

SUMMARY OF SENSITIVITY CHECKS

Method	Millions					C	R	Rate of Return
	Δh	Δm	Δu	Δt	S			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Basis of Comparison								
Method 6 from Table B-2	$20.0	$0.61	$68.4	23.6	$ 90.2	$-2.02	5.51	30.2%
Sensitivity Checks								
1 Use 30-year study period instead of 25	20.0	0.61	78.3	27.0	106.4	-2.14	6.32	30.2
2 Use 5% interest rate instead of 6%	20.0	0.68	77.1	26.6	104.3	-2.12	6.21	30.2
3 Assume 5% mileage saving on alternative 1	20.0	0.61	71.8	24.6	95.4	-2.08	5.77	31.3
4 Assume exponential traffic increase*	20.0	0.61	69.4	23.7	91.4	-2.06	5.57	25.2
5 Include maintenance and resurfacing savings from use of rural road for freeway route**	20.0	0.21	68.4	23.6	90.6	-2.04	5.53	30.4
6 Same as No. 5 but assume resurfacing of old road in year 10 rather than year 1	20.0	0.28	68.4	23.6	90.5	-2.04	5.52	30.3
7 Assume 5% added mileage requirement on alternative 1	20.0	0.61	65.3	22.5	85.2	-1.98	5.26	29.0
8 Use 7% interest rate instead of 6%	20.0	0.56	60.9	21.0	78.2	-1.92	4.91	30.2
9 Use 5 mph higher speed estimate on alternative 0	20.0	0.61	60.3	15.8	68.1	-2.52	4.40	25.2
10 Use V = $0.90 instead of $1.80	20.0	0.61	68.4	23.6	69.0	-2.02	4.45	25.4

Note: Δh = initial cost increment
Δm, Δu, and Δt = incremental present worths of maintenance costs; user savings in operating, truck time, and accident costs; and time savings
S = transportation cost savings
C = cost of time
R = benefit/cost ratio.

* The traffic increase is here estimated at 8.7% annually both within and beyond the period of the state's original traffic estimate (1960-1980). All other methods and sensitivity checks assume a linear traffic growth of +1,540 ADT annually on the ADT for alternative 0 (see Table B-1).

** Assumed effect is to decrease incremental maintenance costs from $48,000 to $29,000 annually, and to add $170,000 savings in year 1 for avoidance of resurfacing costs on old route (21.2 lane miles × $8,000 per lane mile for a 2-inch resurfacing).

Sensitivity Checks

A series of ten sensitivity checks has been devised (Table B-5), chosen as the most interesting among many conceivable modifications to the procedures and data of Method 6 in Table B-2. These variations on Method 6 illustrate the sensitivity of the economy study results to some of the conclusions reached in Appendix A with regard to choice of interest rate, study period, resurfacing costs, and other variables. Checks 1 through 9 are arranged for convenience in the order of decreasing transportation cost savings; they are self-explanatory and need not be elaborated.

Sensitivity check 10 illustrates the changes in economic indexes (compared with Method 6 of Table B-2) that result from the use of $.90/hr instead of $1.80/hr as the value of passenger car time. Note the sizable change in the transportation cost savings (-$21.2 million) and the benefit/cost ratio (-1.06) caused by using a lower value of time. It is also of interest, though not shown on Table B-5, that the percentage of user savings due to passenger car time savings drops from 38 percent in Method 6 to 24 percent in sensitivity check 10, through using a value of time equal to $.90/hr rather than $1.80/hr. The advantages of decreasing the reliance on the value of time as a component of user savings are noted in the introduction to the text; this is merely a numerical illustration of such advantages.

Utilization of Economic Analysis by State Highway Departments

DAVID M. GLANCY
District of Columbia Department of Highways and Traffic

•DURING calendar year 1962 the highway departments for the fifty states plus the District of Columbia and Puerto Rico were surveyed by mailed questionnaire on their use of engineering economic analysis. Replies were received from all but two. This report is an analysis of the questionnaires returned. It has been prepared in an effort to portray the general use and the "State of the art." In this report no state is identified, but each state should be able to compare its economic analysis practices with the general practices of the other states reporting. The questions asked in the questionnaire are listed in the Appendix.

Figure 1 shows the frequency of use of economic analysis by state highway department organizational units by Federal-aid systems. In an effort to indicate the average use, the frequency categories of the questionnaire, which are shown in Figure 1, were weighted. The weight given each frequency category was as follows:

Frequency Category	Weight
Always	1.00
Generally	0.75
Occasionally	0.50
Seldom	0.25
Never	0.00

The resulting weighted average use by systems and organizational unit is shown in Figure 2.

As detailed an analysis of use by projects was not possible. This was due to an apparent misunderstanding of the questionnaire instructions. Over half the returns indicated some use of economic analysis but failed to indicate a frequency of use as requested. The percentage of states which use economic analysis upon some occasion for various types of projects is given in Table 1.

A comparison of the data in Figure 1 with that in Table 1 indicates inconsistencies in completing the questionnaires. To illustrate these inconsistencies the projects given in Table 1 were grouped by the organizational units whose responsibility they would normally be. The percentage that economic analysis was reported used by organizational units was averaged for all Federal-aid systems. This percentage was compared with the reported use by projects. This comparison is given in Table 2. Reported use by projects specifically listed in the questionnaire was considerably higher than the reported use by organizational units except for advance planning and preliminary design projects. Conversely, it appears that little effort was made to indicate use by projects not specifically listed in the questionnaire.

The benefit-cost ratio method of analysis was reported used by the vast majority of states. In fact, only one state reported not using that method and one other state failed to indicate the method used. Several organizational units reported using several other methods concomitant with the benefit-cost ratio method. This raises a question on the

Paper sponsored by Committee on Highway Engineering Economy.

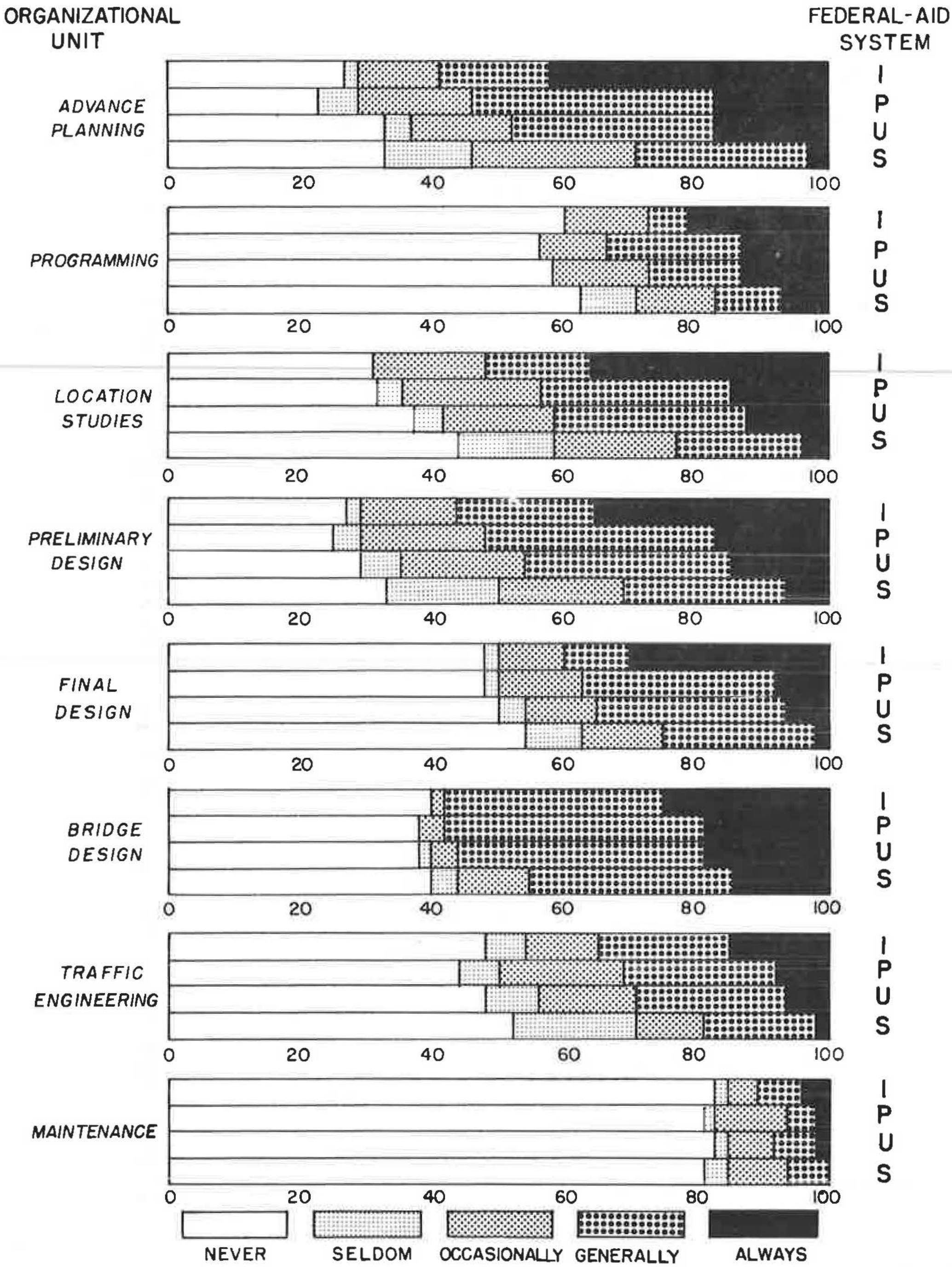

Figure 1. Percentage use of economy analysis by Federal-aid system, organizational unit and frequency category.

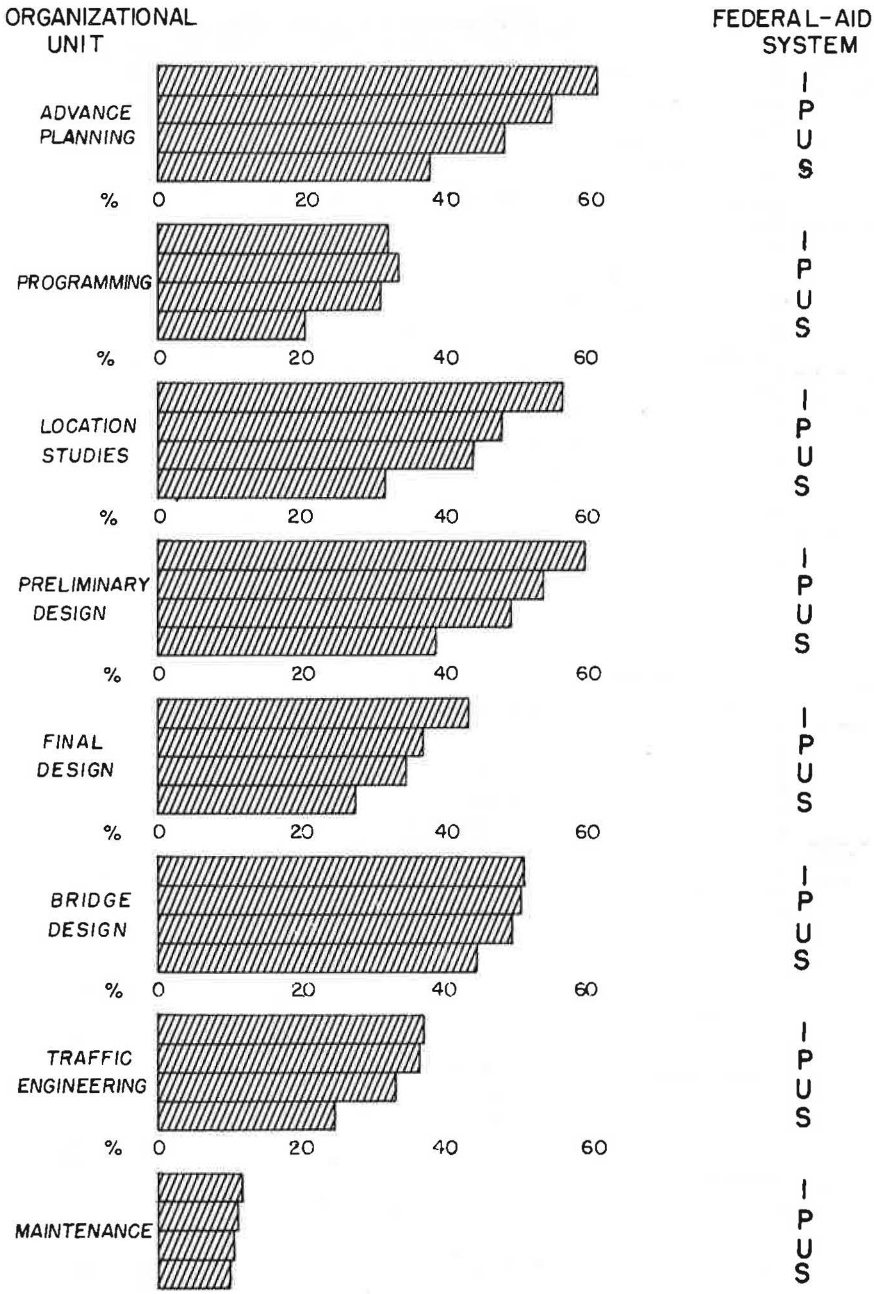

Figure 2. Weighted average use of economy analysis by Federal-aid system and organizational unit.

TABLE 1

PERCENTAGE OF STATES USING ECONOMIC ANALYSIS UPON SOME OCCASION

Type of Project	Percent Usage
Priority for construction programming	82
Alternate route location studies	98
Alternate network studies	78
Alternate studies varying design speed	76
Alternate stage construction studies	80
Alternate limited access point studies	78
Frontage road vs direct purchase of limited access right-of-way studies	74
Alternate pavement materials studies	70
Alternate cross section studies	80
Alternate drainage studies	88
Alternate traffic control signal types and/or signs for intersections	82
Alternate geometric controls for intersection traffic	86
Alternate navigation clearance studies	70
Others: Alternate bridge designs	2
Alternate interchange analysis	2
Maintenance betterment projects	2
Not indicated	2

TABLE 2

COMPARISON OF REPORTED USE BY ORGANIZATIONAL UNITS AND BY PROJECTS

Organizational Unit	Use	Project	Use	Diff.
Advance planning	71	Alternate network studies	78	7
Programming	41	Priority for construction programming	82	41
Location studies	64	Alternate route location studies	98	34
Preliminary design	71	Alternate studies varying design speed	76	5
		Alternate stage construction studies	80	9
		Alternate limited access point studies	78	7
		Frontage road vs direct purchase of limited access right-of-way	74	3
		Alternate cross section studies	80	9
		Alternate navigation clearance studies	70	-1
		Others: Alternate interchange analysis	2	-69
Final design	50	Alternate pavement materials studies	70	20
		Alternate drainage studies	88	38
		Alternate geometric controls for intersection traffic	86	36
Bridge design	61	Others: Alternate bridge designs	2	-59
Traffic engineering	52	Alternate traffic control signal types and/or signs for intersections	82	30
Maintenance	18	Others: Maintenance betterment projects	2	-16

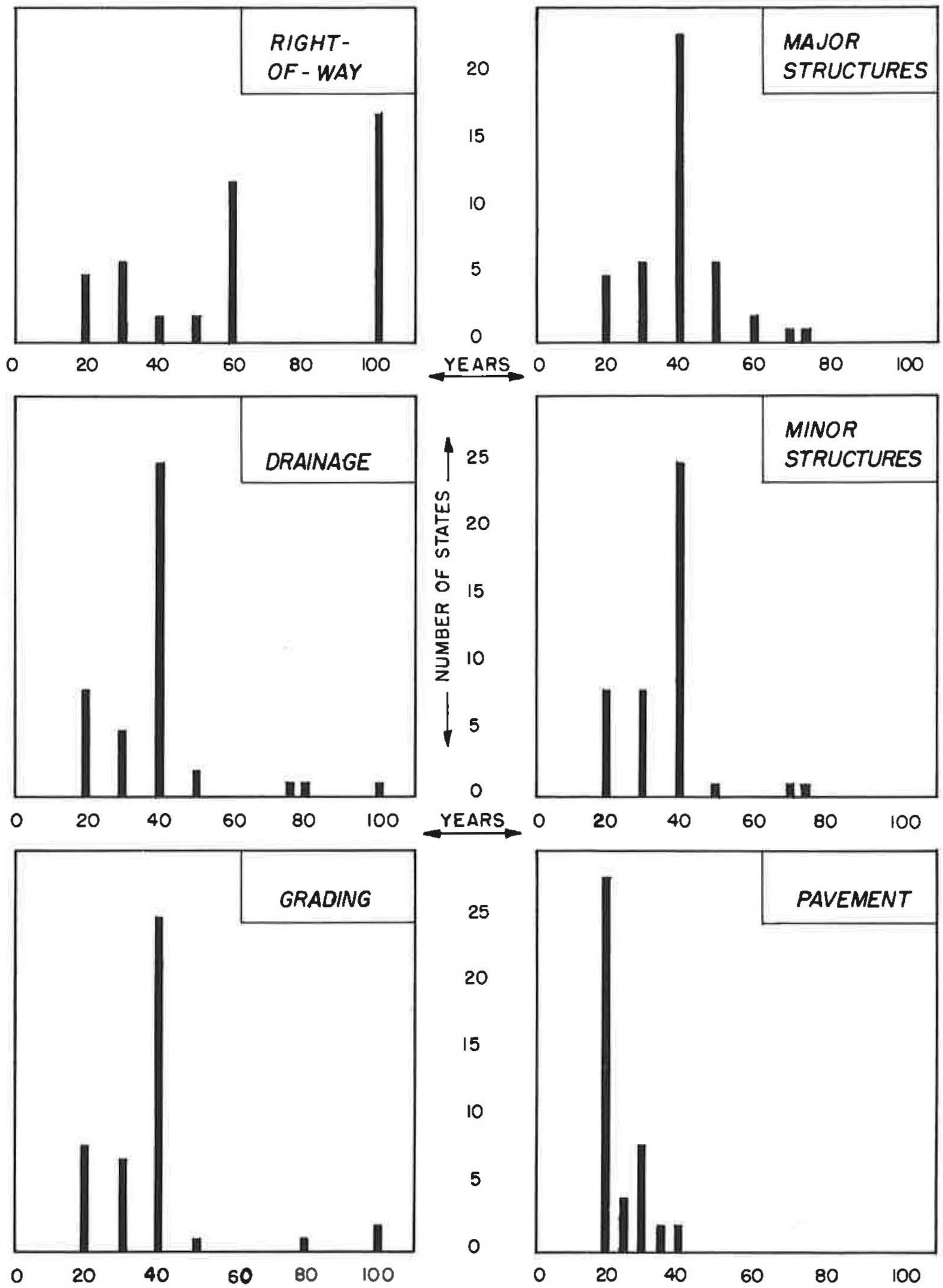

Figure 3. Service lives used.

TABLE 3

PERCENTAGE USING VARIOUS INTEREST RATES IN ECONOMIC ANALYSIS

Organizational Unit	0%	2 to 3¾%	4 to 7%
Advance planning	31.6	28.9	39.5
Programming	39.1	26.1	34.8
Location studies	30.3	18.2	51.5
Preliminary design	40.0	20.0	40.0
Final design	66.7	25.0	8.3
Bridge design	50.0	20.0	30.0
Traffic engineering	56.0	16.0	28.0
Maintenance	88.9	11.1	0.0
Avg.	45.2	21.7	33.1

use of economic analysis. Are several methods which yield different results used to aid the decision maker or to enable him to justify any decision made?

From the reported methods of analysis and from the reported user unit costs used it is apparent that most states follow the AASHO "Red Book" when they make economic analyses. Several states, however, reported use of fixed user unit costs.

Major determinants in an economic analysis, in addition to user costs, are the assumed service life of various highway elements and the rate of interest use. In this survey six reporting states failed to indicate the service life or study period used. The values used by the other 44 are shown in Figure 3. As indicated by the graphs, there is considerable difference of opinion on the values to use. The survey indicated that only four states make any effort to deal with salvage value. The other 40 which reported service life values either did not use a study period or used service life values equal to the study period.

Table 3 gives the reported use of interest rates by organizational units. As Table 3 indicates, there are differences of opinion on the rate of interest to use not only among states but also among organizational units within the states. The survey showed 22 incidents of different rates of interest being used by units within departments. Several states added comments on their returns in regard to interest; e.g., "bond issues not permitted by state law," "on pay as you go basis," etc.

In conclusion, it appears to the Committee that due to some inconsistencies in the reported data and to the inherent weakness of mailed questionnaires, specific findings are not possible. General conclusions, however, can be drawn. In the opinion of the Committee the following general conclusions of this survey can be made:

1. The fullest possible use of economic analysis is not made by state highway departments.
2. There appears to be some incidence of misuse and/or misunderstanding of economic analysis theory.
3. A greater unanimity of opinion on economic analysis techniques not only among states but also within individual states would be desirable.
4. Additional research on the practices and procedures would be useful.

Appendix

The following nine questions were contained in the Committee's questionnaire. Each state department was asked to answer for each of the eight organizational units shown in the report.

1. To what extent do you analyze projects and components for economic feasibility?
2. What general method do you use?
3. What life (in years) do you assign for analysis to right of way, grading drainage, minor structures, major structures, and pavement? 3A. If you do not use individual service lives noted above, indicate composite service life or study period (not service life).
4. What rate of interest do you use customarily and in special cases (indicate nature)? Minimum acceptable rate of return?
5. For the vehicle population, do you use passenger cars only, passenger cars and individual classes of commercial vehicles, passenger cars and composite of commercial vehicles, equivalent vehicles or others?

6. Do you assign values (indicate amount if pertinent) to running cost of vehicle(s), accidents, travel time of passenger cars and commercial vehicles, comfort and convenience, and non-user consequences?

7. Type computer on which you have programmed analysis?

8. Following is a check list of specific areas of highway engineering. Please designate amount of your usage of economy analysis by letter code as follows: Always-A, Generally-G, Occasionally-O, Seldom-S, Never-N. Leave blank those items not pertinent to your unit. A. Highway Systems. Interstate, F. A. Primary, F. A. Urban, F. A. Secondary, State Primary, State Secondary, others. B. Projects (see Table 1).

9. Have you an unusual economic study or theory you could present in the form of a paper?

Discussion

EUGENE L. GRANT, Professor of Economics of Engineering, Emeritus, Stanford University (and Chairman, Committee on Highway Engineering Economy, 1960-64).—This interesting and important paper is the result of the work of an ad hoc subcommittee of the Committee on Highway Engineering Economy. The questionnaire project was carried out with the approval and sponsorship of the Highway Research Board. Particular credit should go to Subcommittee Chairman Evan Gardner for directing and carrying out this project, and to Mr. Glancy for analyzing the information from the completed questionnaires. A complete detailed tabulation prepared by Mr. Glancy has been made available to the cooperating agencies through the Highway Research Board. The present paper is a brief summary of some of the high spots of the information given in his detailed tabulation.

This survey differs from many surveys by questionnaire in having a negligible sampling error in its conclusions. Questionnaires were sent to all of the appropriate agencies and 50 out of 52 responded.

Nevertheless, there is a fair amount of informal evidence that a bias may have been present in some of the answers to the first question: "To what extent do you analyze projects and components for economic feasibility?" In answering such a question that calls for an opinion, some respondents may want to make what seems to them as good a showing as possible for their organizations and may answer, say, "generally" in cases where "seldom" or "occasionally" may be a more accurate description of actual practice. Conversations with highway engineers who are familiar with the practices in a number of the states have convinced me that a bias of this type did exist and that this bias should be recognized in interpreting Mr. Glancy's Figure 1.

However, the "never" answers to the first question presumably involve no such bias. The unshaded portion of Figure 1, which represents the "never" answers, appears to be, on the average, something more than 40 percent of the entire graph. In view of the large public expenditures for highways in the United States, this high percentage should be quite distressing to anyone who believes in the reasonable proposition that better decisions on highway programming, location, and design can be made with economic analysis than without it.

When a condition is unsatisfactory, a relevant question is whether matters are getting better or worse. On this topic, the writer has the impression, which cannot be supported by any statistical evidence, that the use of the techniques of engineering economy by state highway agencies has been increasing; if the questionnaire had been five years earlier, the "never" answers would have been even more numerous. The writer also has the impression that the quality of the economic analysis is improving where such analysis is being made. Observations also indicate that a considerable fraction of the economic analysis made by state agencies in recent years has been made only because of requirements of the U. S. Bureau of Public Roads; if the state agencies had been free to do as they pleased, no economic analysis at all would have been made. There are, however, some notable exceptions; certain state agencies have done excellent work in this area on their own initiative.

The remaining comments deal with Table 3, which records the use of various interest rates in economic analysis for highways. These comments were inspired by two other papers presented at the HRB 43rd (1964) Annual Meeting. There are many good reasons why the 33 percent of agencies and organizational units reported as using interest rates of 4 to 7 percent are using a much sounder basis for highway decisions than the 45 percent reported as using no interest or the 22 percent using 2 to 3 ¾ percent. Two of the reasons were brought to mind by the two papers.

The interest rate selected for such studies is, in effect, the minimum attractive rate of return. The use of a 0 percent interest rate has the result of making all proposed increments of investment appear to be attractive if they yield more than 0 percent. Because of the many opportunities for productive investment in the American economic system, each increment of investment in highway improvements that yields, say, only 3 percent, has the effect of preventing some other investment—possibly one in highways or possibly one elsewhere in the economic system—that will be much more productive. A noteworthy illustration of this point was given in the paper entitled "Sufficiency Rating by Investment Opportunity," by E. H. Gardner and J. B. Chiles, which describes a computerized method for determining the order of priority over a period of years for proposed highway improvements over an entire state highway system. In this method, a minimum attractive rate of return (interest rate) of 20 percent was used. This high rate, in effect, reflected the opportunity cost of capital within the state highway system, considering the limitation of highway funds and the many productive projects competing for these limited funds.

Another session at the 43rd Annual Meeting was a conference session on the sociological effect of highways. Although no one at this session mentioned interest rates in highway economy studies, some of the types of matters presented seemed to be quite relevant in relation to the issue of the best interest rate to use in specific kinds of studies.

In principle, an economic analysis made to influence a decision on a public works investment should consider the prospective consequences of the investment "to whomsoever they may accrue." Wherever practicable, these consequences should be evaluated in monetary terms—the only terms in which diverse consequences can be made commensurable. For many types of public works, including some types of highway improvements, it may be evident that there will be a mixture of favorable consequences to a portion of the public and unfavorable consequences to another portion.

A good example of unfavorable consequences was given by Miss Barbara Kemp, of the District of Columbia Health and Welfare Council, who described the results obtained from interviews with a sample of persons who would be dislocated by a proposed freeway project in the District of Columbia. She reported much resentment from a number of persons in low-income groups who felt that they would be badly hurt and receive no benefits from a project that they viewed as intended chiefly to help well-to-do dwellers in the suburbs. Some persons interviewed had lived for many years in the areas affected. They felt that condemnation for freeway purposes of the areas where they were living would force them into less congenial surroundings and also would increase their living costs.

The foregoing bears on one facet of Mr. Glancy's Table 3, which shows that different organizational units within a given highway agency often employ different interest rates in their economic analyses. On first impression, an observer might conclude that it is undesirable to have this type of difference in decision-making criteria within a single highway agency. Doubtless, many of the differences shown in Table 3 are entirely capricious and have no rational basis.

Nevertheless, there are sound reasons why one might defend the use of different minimum attractive rates of return for different types of highway investment projects that are competing for the same limited funds. A proposed investment that has a mixture of favorable and unfavorable consequences to the citizenry, such as the proposed freeway project in the District of Columbia mentioned by Miss Kemp, might well be subject to more severe decision-making criteria than a proposed investment where all of the prospective consequences are favorable.

CLARKSON H. OGLESBY, Professor of Civil Engineering, Stanford University.— Messrs. Gardner and Glancy have performed a valuable service in preparing and circulating the comprehensive questionnaire on engineering-economy practices of state highway departments and in analyzing its results. Thanks are also due to officials of the state highway departments for their cooperation in filling out yet another detailed questionnaire. As a result of these efforts there is now a far better picture of the level of attention given to economic analysis at the state level.

Designers of the questionnaire worked on the basic premise that economic decisions are made in all phases of highway planning, design, and operations and at all levels of authority. Too often highway engineers have assumed that economic decisions concern only such sticky subjects as programming, budgeting, and controversial route locations, which are the province of the "top brass." In reality, however, the design engineer who selects a culvert or a pavement section, the traffic engineer who recommends on signs or signals, and the maintenance supervisor who decides how often to mow the roadside makes a decision that has economic consequences. In all these cases the decisions may alter costs to the highway agency, the traveling public, and the non-user. Yet the results make clear that in these areas in particular, formal appraisals of the dollar consequences of decisions seldom are made.

Taken as a whole, the questionnaire findings are disappointing to those who feel that economic analysis can provide one of the important guides for highway decision makers. If such measures carried much weight, a high proportion of the reporting agencies would have indicated that they used them "always" or "generally." Stated differently, if dollar measures (other than the total money involved) were important to decision makers, a means for securing them would have been incorporated into the "routines" of highway agencies. The results indicate, however that most states apply economic measures only to "exceptions."

Even though the survey results indicate that little attention is given to economic analysis, it may be that they still paint too favorable a picture. Being "for economic analysis" is parallel to being "against sin." Therefore it would be a natural tendency (to which college professors are not immune) to report "always" rather than "generally," "generally" rather than "occasionally," and so on.

There is strong evidence elsewhere to support the questionnaire findings that highway decision makers give relatively little weight to the matter of long-run economy. Only two examples are cited here, but the list easily could be expanded.

Example 1. The "Manual of Uniform Traffic Control Devices" (1) is a monumental work, and rightly has worldwide acceptance. However, in almost no instance do the recommended warrants for justifying traffic control devices evaluate the cost in the long run to highway agencies and road users, although these costs are substantial. For example, a recent study (2) indicated that, on converting a normal intersection carrying 10,000 vehicles per day from two-way to four-way stop sign control, motor vehicle operating costs (over and above driving straight through) rose from $6,000 to $14,000 per year, an increase of $8,000 annually. A second instance (2) dealt with installing a traffic signal at a "T" intersection on a busy thoroughfare to accommodate a small volume of entering traffic. Here the costs associated with signal installation and vehicle operation, including those for an increase in accidents, rose more than $20,000 per year over those when entry was controlled by a stop sign. It would seem that consideration of economic facts such as these would bring better traffic engineering decisions and also provide aid to engineers trying to resist pressures for unwise or unnecessary installations.

Example 2. The "Manual on Advance Road Programs" (3) is an excellent document, and is one of several indications that county road management is becoming professional rather than political. It states (p. 5):

> Advance road programming should be a continuous activity of efficient road management— whose aim is to serve the public through provision of adequate, safe, yet economic road travel. The formulation of plans for advance road planning is the joint

responsibility of the county engineer and the county board, representing the team for road management.

In the detailed procedures for evaluating the county road system, the manual makes no reference to formal economic analysis. Rather, on the basis of a physical inventory, a service rating and a condition rating are combined to produce a priority rating. This rating, combined with a financial analysis, leads to an improvement program and a schedule of priorities. Nowhere is provision made to answer the three basic economic questions of "Why do this project at all?" "Why do it now?" and "Why do it this way?" With the counties so desperately in need of funds for road improvement, it would seem that answers to these questions are basic to reaching sound decisions.

Results of the questionnaire and other evidence, including the examples cited here, have convinced the writer that economic analysis is seldom employed in highway decision making. Even so, a second important question is this: "Are the economic analyses that now are being made correct in technique and based on realistic data and assumptions?"

An earlier critique on 85 alternate route location studies has indicated a number of common errors (4). More recently, however, Charles Dale, Research Engineer of the U. S. Bureau of Public Roads, analyzed 130 economy studies prepared either by state highway departments or by their consultants. These were submitted to the Bureau in 1962 by 34 states, the District of Columbia, and Puerto Rico. Projects analyzed included (a) alternate highway locations, (b) alternate river crossing schemes, (c) grade-separation studies, and (d) surface type determinations

Mr. Dale has graciously supplied a summary of his findings. A list of eight items drawn from his analysis is pertinent to this discussion, as follows:

1. Of the 130 reports, 95 had road-user benefit analyses of the proposed alternates. The remaining 35 did not, although in 27 of them different alternatives would develop different road-user consequences. For the other 8 reports, which dealt with alternative pavement types, road-user consequences were not considered to be a factor.

2. Of the 95 reports which included a road-user analysis, the benefit-cost ratio method of solution was used in 68 instances. The remaining 27 employed the total annual transportation cost method. A few of the benefit-cost ratio studies also compared the projects by either the rate of return or total annual transportation cost methods.

3. Sixty of the 95 reports based on road-user benefit analysis established annual capital highway costs. Of these, 41 employed different service lives for the various components of the highway (e.g., right-of-way, structures, surfaces). For the other 19, a single analysis period was chosen (usually 30 to 40 years).

4. Accident costs were included as part of the total road-user costs in only five reports (representing two states).

5. Highway maintenance costs were included in 52 of the 95 reports having a road-user benefit analysis.

6. Generally, road-user benefits were calculated for design-year or terminal-year traffic, and were assumed to be uniform for the entire analysis period. The terminal year in most cases was 1975.

7. Only 64 of the 95 reports that included road-user benefit analysis stated the specific rate of interest used in the analysis. The percentage distribution of the stated interest rates was as follows:

Interest Rate (%)	Reports Using (%)
0.0	= 20
0.1-3.9	= 22
4.0-5.9	= 45
6.0-7.0	= 13
over 7.0 percent	= 0

8. Of the 68 analyses that used the benefit-cost ratio method, a "second benefit ratio," also called an incremental benefit-cost ratio, appeared in only 7 reports; yet all but 5 studies considered multiple alternatives.

The first three items are primarily reports on techniques for analysis or a statement of assumptions. Although analysts may argue the merits of some over others, all, if properly done, will give correct results. This has been demonstrated, among other places, by Grant and Oglesby (5).

Item 4 indicates that only 5 reports considered accident costs; item 5 shows that numerous others neglected maintenance costs. Here the basic problem is lack of suitable data. In these and in many other areas, much research is needed before dependable values are forthcoming; certainly it would be improper to make these omissions a basis for criticism under present circumstances.

Item 6 indicates that in many reports traffic for the design year was employed in computing annual benefits without discounting. If, as is usually the case, substantial traffic growth is assumed for the design year, an error results which greatly overstates the benefits. For example, if it is assumed that traffic doubles in a 20-year design period and 7 percent is an appropriate interest rate, then benefits are overstated more than 40 percent.

Item 7 gives the spread of interest rates employed in the studies. There are strong arguments to the effect that these rates are too low and may result in wrong decisions. These arguments are presented by Grant (6) and Winfrey (7) and are repeated here.

It is disturbing also to find that almost one-third of the reports failed to state the interest rate employed. This knowledge is of vital importance to decision makers and others who might review the reports or the decisions based on them. Stated bluntly, such omissions show poor report writing and are a reflection on the engineers who did the work.

Item 8 indicates that a preponderance of the analysts blundered by failing to consider the second or incremental benefit-cost ratio. The effect, in those instances where a higher-cost alternative was recommended, may have been to propose spending money for works that would not show the stipulated minimum attractive rate of return. Grant and Oglesby (5) treat this subject in detail.

Where reports stated the sources of the procedure for analysis, almost all referred to the "Red Book" (8). This work suggests, in Appendix B, pp. 151-152, that incremental analyses be made and gives an example of the procedure to follow. It may be that the trouble lies in the wording of the "Red Book," which may seem to make incremental analysis permissible rather than mandatory. In any event, analysts must recognize that they are in error if they make comparisons among several separate and distinct solutions to the same problem without including an incremental analysis.

This discussion has attempted to summarize the "state of the art" of highway engineering economy as shown by the results of the questionnaire and the analysis of 130 recently completed studies. It should be clear to all concerned that much is yet to be done to fill the gaps in knowledge of the economic consequences of highway improvement. In addition, there is a great need to adapt the already developed principles and techniques of engineering economy to highway situations. Also, much work lies ahead if existing procedures are to be corrected and refined and new ones developed in areas not now covered. This effort cannot be left to a handful of engineers and educators or to the Highway Research Board Committee on Engineering Economy. It requires the interest and support of highway engineers at all levels of authority and in all agencies.

In conclusion, one word of caution: in enthusiasm to promote serious attention to engineering economy as a working tool for highway engineers and administrators, there must be recognition that it is not an end in itself, nor can it stand alone. Rather, economic analysis provides dollar answers where dollars represent an appropriate measure of the consequences of highway improvement. As such, it helps the decision maker narrow the area of uncertainty surrounding the choices he must make, and thereby can aid him as he tries to make better use of the money that the public is devoting to highways.

References

1. Manual of Uniform Traffic Control Devices for Streets and Highways. Nat. Joint Comm. on Uniform Traffic Control Devices, 1961.
2. Application of the Principles of Engineering Economy to Highway Improvements. Stanford Univ., Proj. on Eng. Econ. Planning, March 1964.
3. Manual on Advance Road Programs. Nat. Assoc. of County Engrs, County Road Management Guide Ser., Oct. 1960.
4. Grant, E. L., and Oglesby, C. H. A Critique of Some Recent Economic Studies Comparing Alternate Highway Locations. Highway Research Board Proc., Vol. 39, pp. 1-8, 1960.
5. Grant, E. L., and Oglesby, C. H. Economy Studies for Highways. Highway Research Board Bull. 306, pp. 23-38, 1961.
6. Grant, E. L. Interest and the Rate of Return on Investments. Highway Research Board Spec. Rept. 56, pp. 82-90, 1960.
7. Winfrey, Robley. Highway Engineering Handbook. Sect. 3. New York, McGraw-Hill, 1960.
8. Road User Benefit Analysis for Highway Improvements. AASHO, 1960.

A Study of Annual Costs of Flexible and Rigid Pavements for State Highways In California

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This study provides the results for more than 600 solutions of annual costs of pavements in which the effect on the annual cost of eight major variables is clearly set forth. The variables included in the study consisted of: (1) subgrade quality for six subgrade resistance values; (2) traffic indexes for light, medium, and heavy traffic; (3) contract bid prices for all state highway pavement construction in California in 1958 and 1960 in the low range (10 percentile value), in the high range (90 percentile value), and for the arithmetic mean of all bid prices; (4) interest rates of 3 percent and 6 percent; (5) a service life of initial pavement of 13 years and 18 years was used for flexible pavements and 18 years and 26 years for rigid pavements and a service life of 13 years for the first and second asphalt concrete resurfacing was used for both flexible and rigid pavements; (6) the annual costs were computed for analysis periods of 26 years and 35 years; (7) average maintenance costs for California flexible and rigid pavements were used in the primary study and the effect of doubling and tripling the maintenance cost of flexible pavements versus no change in these costs for rigid pavements was determined on a sampling basis; and (8) a total shoulder width of 22 ft and a 2-lane pavement width of 24 ft was used in the primary study and an analysis of the effect of reduced shoulder width for 6-lane and 8-lane freeways was made on a sampling basis.

The results of the study indicated that for subgrades with resistance values (R-values) in the medium range of 25 to 60, the annual costs of flexible versus rigid pavements vary considerably, depending on the design values for the traffic index, the costs of the initial construction, and the resurfacing and maintenance costs of the particular pavement. For subgrades with R-values in the high range (above 60) the annual costs of the flexible pavements were always lower than the corresponding costs for rigid pavements. The annual cost of light-duty pavements in the majority of the solutions tended to favor the selection of flexible pavements, whereas for heavy-duty highways the majority of the solutions tended to favor the selection of rigid pavements. Resurfacing costs can have an important effect on the selection of pavement type. If a high frequency of resurfacing is expected for either the flexible or rigid type under conditions where a low frequency of resurfacing is required for the alternate type, the pavement with the longer service life will be favored on an annual cost basis. Varying the interest rates and the analysis periods influences the annual costs considerably for the two pavement types, but this effect is not as important as the effect of variations in subgrade quality, the traffic index, and the change in initial construction and resurfacing costs. The effect of varying the annual maintenance costs of the two pavement types resulted in a minor change in annual costs. Thus, the average annual maintenance costs for the two types of pavement amounted to only about 3 to 5 percent of the total annual pavement cost, and even using a

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maintenance cost for flexible pavements 3 times greater than the annual average maintenance costs resulted in no significant change in terms of the total annual costs of flexible versus rigid pavements.

This study indicates the importance of making a complete cost analysis in the selection of pavement types. The relative importance of the eight major variables in an analysis of annual costs is clearly shown in table and chart form. Although other factors, such as traffic safety, skid resistance, light-reflecting properties, esthetics, noise levels, and political decisions, should be considered in the selection of pavement types, there is evident need for adoption of a standard method for the determination of the annual costs of pavements and of giving adequate weight to annual costs in the selection of pavement types.

•A MAJOR DECISION confronting the highway engineer and administrator responsible for the planning and design of pavements for modern freeways and expressways is the selection of the pavement type, rigid or flexible, which will provide the highway user with the best possible service at the lowest cost. This selection is complicated by many factors and considerations which make it most difficult to reach a decision which is fully documented and acceptable to all interested parties.

In 1960 a report (1) prepared by the AASHO Special Committee on Project Procedures was published in which five principal factors and ten secondary factors governing the selection of pavement type were listed and discussed. The five principal factors and the ten secondary factors considered by the committee to have a major or an occasional influence in the selection of pavement type are as follows: principal factors—(1) traffic, (2) soils characteristics, (3) weather, (4) performance of similar pavements in the area, and (5) economics or cost comparison; secondary factors—(1) adjacent existing pavement, (2) stage construction, (3) depressed, surface or elevated design, (4) highway system, (5) conservation of aggregates, (6) stimulate competition, (7) construction and maintenance considerations, (8) local preference, (9) traffic safety—skid resistance, etc., and (10) availability and adaptation of local materials.

The AASHO committee did not propose a formula or a standard procedure for the selection of paving type. In the report the committee stated that "To avoid criticism, if that is possible, any decision as to paving type to be used should be firmly based. Judicious and prudent consideration and evaluation of the governing factors will result in a firm base for a decision on paving type."

The California Division of Highways and many other highway departments require an economic analysis or cost comparison as a major factor in the justification of pavement type. In 1963 the California Division of Highways adopted a new method and new cost items in making pavement cost comparisons. These new cost items have been incorporated in the study covered by this paper.

It is the contention of the authors that the principal factors proposed by the AASHO committee can be evaluated on a reasonably sound, rational and factual basis, using California pavement design formulas, and a basic formula for making pavement cost comparisons. This paper consists primarily of a broadly based investigation of the effect on pavement costs of the many factors and variables involved in the structural design of rigid and flexible pavements; the effect of the wide variations in the unit prices of various items for 155 paving projects in California for which contracts were awarded in 1960; and the effect of variations in the service life of flexible and rigid pavements, the interest rate and in the analysis period. The investigation is of the type referred to by economists as a sensitivity study.

For this study 144 pavement and shoulder design sections were developed based on the California Division of Highways rigid and flexible pavement design procedures (2). The structural design was based primarily (a) upon the resistance (R-value) of the subgrade soil, and (b) upon the Traffic Index (TI) for a 20-yr period. Six different subgrade soils ranging from R 5, very poor, to R 80, excellent, and three traffic design loads, TI = 8.5 (light-duty), TI = 10.0 (medium-duty) and TI = 11.5 (heavy-duty) were used for the study. For the portland cement concrete pavements, the standard 4-in. thickness of cement-treated base was used in this study. For the asphalt concrete pavements, the structural design was determined for three different bases: crushed stone, standard cement treated and heavy cement treated. Shoulder designs were developed for each pavement type and for each soil type and for the three traffic design loads.

It was assumed that the same subgrade construction and preparation would be required for both rigid and flexible pavement construction. In locations where subsurface water and unusual soil conditions require a special subsurface drainage design, such as the use of a permeable blanket, 1 ft in depth over the full width of the roadway, it was assumed that the same construction would be required for both rigid and flexible pavements. It is recognized, however, that unusual foundation conditions might require different subgrade treatment for the two pavement types and that this factor, which is not covered by this study, may sometimes be a controlling one in the selection of pavement type.

METHOD FOR DETERMINING ANNUAL HIGHWAY COSTS

The determination of annual highway costs has been the subject of special study and of reports by Highway Research Board committees and by individual investigators since 1920, the year the Board was established. It is significant that the Committee on Economic Theory of Highway Improvements with Dean T. R. Agg as Chairman was listed as the No. 1 committee of the Board for many years and that the Committee on Structural Design of Roads with A. T. Goldbeck as chairman was listed as the No. 2 committee. The senior author of this paper was privileged to be closely associated with Dean Agg for 25 years in making various types of economic studies. The basic principles established in those early studies played an important role in the selection of the method of analysis adopted for this study.

Dean Agg and his Committee developed procedures for determining the justification of highway improvements in terms of basic engineering economy theory. In the Committee report (3) in 1929, a method for determining the annual costs of highways was presented by Dean Agg as follows:

> The annual cost of a road... may be expressed as the total yearly expenditure that will construct, replace, and maintain in perpetuity in standard serviceable condition any existing road under existing traffic and climatic conditions.

R. H. Baldock (4) has reviewed the methods of determining annual highway costs as reported by Agg in 1929, by C. B Breed in 1934 (5) and by the Stanford Research Institute (SRI) in 1961 (6). After presenting a detailed discussion and evaluation of each method, Baldock proposed a method, patterned after the one developed by SRI, which provides for the payment of the initial construction cost and of future resurfacings on a uniform annual cost basis at a given interest rate in a definite time interval of 40 years. To this is added the average annual maintenance cost.

In June 1963, the California Division of Highways adopted a new method (7) for making economic comparisons of pavement types. The costs for each pavement type using the new method are computed in accordance with the following instructions:

1. All future pavement structural designs shall be based on 20-yr equivalent wheel load (EWL) totals.
2. An appropriate economic analysis period shall be chosen for each project based on the average life to first resurfacing of concrete pavements in the area that served under comparable conditions. In general, this will range from 20 years upward based on present experience.
3. Compound interest at the rate of 5 percent shall be used as necessary to convert all costs to present worth.
4. Initial costs shall be computed for the entire structural section including shoulders for one direction of travel and a length of one mile.
5. Estimated costs of future resurfacing shall be increased by the application of a price trend factor. Based on the California Highway Construction Cost Index, 2 percent compound interest should be used at present.

6. Engineering charges on initial construction shall be omitted, but preliminary and construction engineering charges in connection with resurfacing shall be included. This shall be expressed as a percent of the future resurfacing cost.

7. Estimates of resurfacing cost must include all supplemental work made necessary by the resurfacing. Traffic handling, temporary traffic stripes, replacing permanent traffic stripes, protection or temporary removal of guardrails, adjustments of drainage facilities, and other supplemental work should be carefully estimated.

8. The costs of traffic delay shall be estimated and added to the cost of resurfacing.

9. Maintenance costs shall be included where District records can be used to demonstrate a difference in cost between the two surface types.

10. Salvage values shall be used only as necessary to bring both estimates to the same analysis period, and should be applied to the last resurfacing only.

It should be noted that item 3 provides for a compound interest rate of 5 percent. This rate is used to convert all costs to present worth costs which are then added to the initial construction costs to obtain the total cost for the given type of pavement. Thus, instead of computing a uniform annual cost for each pavement type, the California Division of Highways computes in effect a total equivalent initial cost for each pavement type. In general, the method adopted by the California Division of Highways follows that proposed by Baldock, except that the total costs are expressed as present worth instead of a uniform annual cost.

After a careful review of all of the methods referred to above for computing the costs of pavements, the authors decided that to establish the effect of many cost variables, the annual cost method recommended by Baldock would best serve our purpose for this study. It was further decided that the three new cost items adopted by the California Division of Highways for computing resurfacing costs should be incorporated.

ANNUAL COST FORMULA

The formula recommended by Baldock for determining the annual costs to compare pavement types adopted for this study takes the following form:

$$C = CRF_n \left[A + E_1(PWF_{n_1}) + E_2(PWF_{n_2}) - (1 - \frac{y}{x}) (E_1 \text{ or } E_2)\ PWF_{n_2} \right] + M \quad (1)$$

in which

C = annual cost of a 2-lane mile of pavement and shoulders;
CRF_n = capital recovery factor for an analysis period of n years and for a given interest rate;
A = initial construction cost of pavement and shoulders, per mile;
E_1 = first resurfacing cost, per mile;
n_1 = service life of initial pavement surface, years;
PWF = present worth factor for n_1 or n_2 years for a given interest rate;
E_2 = second resurfacing cost, per mile;
n_2 = number of years after construction to year when second resurfacing is placed;
y = number of years from time of last resurfacing to end of analysis period;
x = estimated life of last resurfacing, years; and
M = average annual maintenance cost per mile.

BASIC COMPONENTS OF FORMULA

The basic components of Eq. 1 are (a) initial construction cost, (b) resurfacing costs, (c) maintenance costs, (d) interest rate, (e) analysis period, (f) service life of initial pavement surface, and (g) service life of resurfacings.

Since a major purpose for making this study was to determine the effect and relative importance of each component in Eq. 1 for computing the annual cost of each pavement type, two or more values were used for each component. The method of assigning values to the components is described in the following discussion of each of the seven components.

Initial Construction Costs—Design Sections

The initial construction cost of each pavement type was computed on the basis of the thickness and composition of the structural design sections and the unit prices for each item in the pavement cross-section which consisted of the pavement surfacing, the base, subbase and the corresponding items for the shoulders.

For this study 144 pavement and shoulder design sections were developed based on the California Division of Highways' rigid and flexible pavement design procedures published in the Division of Highways Planning Manual. The California pavement design procedures are well adapted for making cost comparisions of the type used in this study. The major factors covered by these procedures in developing the structural cross-section for each pavement type are (a) the structural quality of the basement (subgrade) soil which is measured by means of stabilometer and expansion pressure tests and is expressed as the resistance, R-value, of the soil; (b) the traffic over a 20-yr period in terms of an equivalent number of 5,000-lb wheel loads, EWL, expressed as the Traffic Index, TI; and (c) the slab value of the pavement and supporting layer, which in the design of flexible pavements is expressed in terms of the cohesiometer, C, value.

The California pavement structural design method is based on test road data and on observed performance of pavement structures. Hveem and Sherman (8) show that the thickness of flexible pavement required for a wide variety of traffic loads and materials as determined by the California design formula correlated very well (a correlation coefficient of 0.87) with the thickness requirements for the corresponding traffic loads and materials on the 2-yr AASHO Road Test in Illinois.

The structural design sections of rigid pavements investigated in the AASHO Road Test in Illinois are not directly comparable to the structural design sections of rigid pavements in California since the cement-treated base (CTB) used in California was not included in the structural design section of rigid pavements in the AASHO Road Test. However, the performance of the rigid pavements in the AASHO Road Test when compared with the California rigid pavement design for corresponding traffic loads indicated that the California rigid pavement sections are entirely adequate to carry the traffic for which the California pavements are designed.

Probably the best evidence in regard to the reliability of the California structural design procedures in assuring satisfactory performance of the pavements designed according to these procedures is the observed performance of pavements in all parts of California. For the past 12 years, tests have been conducted by the Institute of Transportation and Traffic Engineering under the direction of the senior author to measure the road roughness of both rigid and flexible pavements on state highways in all parts of California. The AASHO Road Test studies showed that road roughness measurements provided the best single indicator of pavement performance and for computing the serviceability index of a given section of pavement. The results of the road roughness measurements in California when compared with the results of similar measurements in other states and on the WASHO and AASHO road tests indicated the excellent structural quality of both the rigid and flexible pavements in California. In the judgment of the authors, the low road roughness readings and the excellent riding quality observed on California pavements provide the best evidence now available of the reliability of the California pavement design procedures to assure satisfactory pavement performance.

The structural design of rigid and flexible pavements for 4-lane freeways in California is shown in Figure 1 for typical pavement and shoulder design sections in cut and in fill. It should be noted that the design of the subbase and base requires a greater with of roadway in the fill section than in the cut section. To simplify the computations for the quantities required for various depths of pavement for cut and fill, the comparisons in this study were made on the basis of a uniform width of pavement for the traveled way of 24 ft and a uniform width for the two shoulders of 14 ft. Since the shoulder

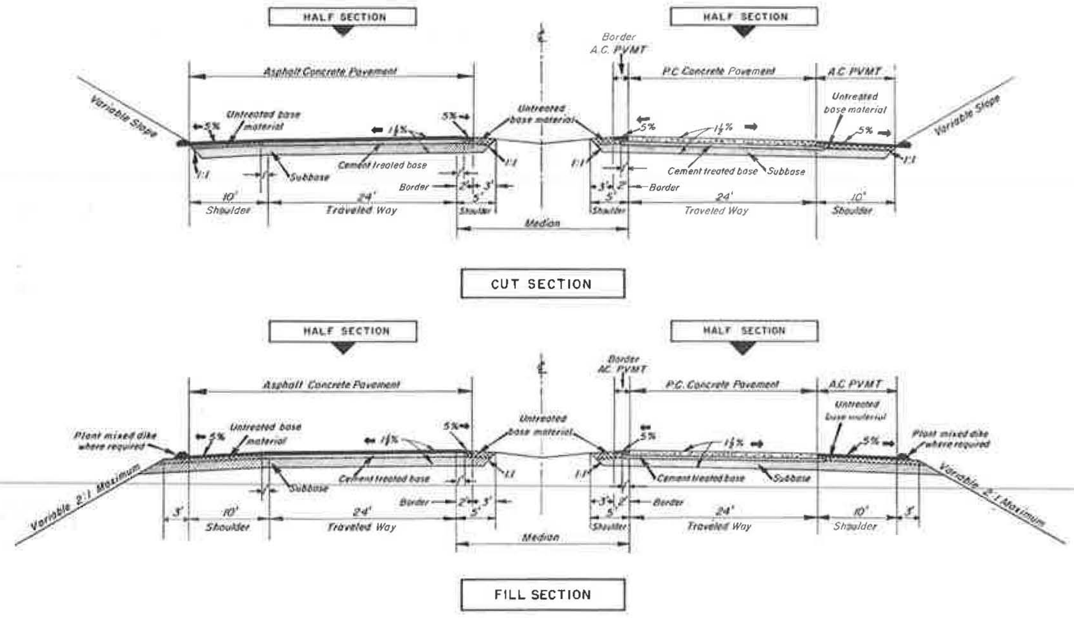

Figure 1. California Division of Highways typical pavement and shoulder design cross-section.

design for both flexible and rigid pavements in California is practically identical for corresponding traffic and soil conditions, the adoption of a uniform width of shoulder did not introduce a significant error in the quantities used or in the cost of the corresponding designs for rigid and flexible pavements.

TABLE 1

RIGID PAVEMENT STRUCTURAL DESIGN SECTIONS FOR VARIOUS SUBGRADE SOIL CONDITIONS AND FOR LIGHT-, MEDIUM-, AND HEAVY-DUTY TRAFFIC

R-Value of Subgrade Soil	Calif. Traffic Index	Rigid Pavement Design Depth (in.)			
		Portland Cement Concrete Surface	Cement-Treated Base[a]	Subbase	Total Depth
R 5	8.5	8	4-B	8	20
	10.0	9	4-A	10	23
	11.5	9	4-A	12	25
R 20	8.5	8	4-B	6	18
	10.0	9	4-A	8	21
	11.5	9	4-A	10	23
R 35	8.5	8	4-B	6	18
	10.0	9	4-A	6	19
	11.5	9	4-A	8	21
R 50	8.5	8	4-B	6	18
	10.0	9	4-A	6	19
	11.5	9	4-A	6	19
R 65	8.5	8	4-B	—	12
	10.0	9	4-A	—	13
	11.5	9	4-A	—	13
R 80	8.5	8	4-B	—	12
	10.0	9	4-A	—	13
	11.5	9	4-A	—	13

[a]The two types of cement treated base used in this study consist of: (1) Type A with 3½ to 6% portland cement by weight of the dry aggregate, and (2) Type B with 2½ to 4½% portland cement by weight of the dry aggregate.

The rigid pavement structural design sections for six subgrade soil types ranging from a very poor R 5 soil to an excellent R 80 soil and for three traffic design loads, TI = 8.5 (light-duty), TI = 10.0 (medium-duty) and TI = 11.5 (heavy-duty) are given in Table 1. For light-duty traffic, a uniform portland cement concrete pavement slab thickness of 8 in. is used in California. For medium-duty and heavy-duty traffic, this thickness is increased to 9 in. It should be noted that a 4-in. cement-treated base (CTB) is used in all of the rigid pavement design sections and that a varying depth of subbase is used, based upon the R-value of the subgrade soil and the Traffic Index.

The flexible pavement structural design sections given in Table 2 were developed for the same R-values for the subgrade soil and the same TI values for traffic used in the design of the rigid pavement sections, except that three types of base courses, crushed stone, standard CTB and heavy CTB, were used in developing

TABLE 2

FLEXIBLE PAVEMENT STRUCTURAL DESIGN SECTIONS FOR VARIOUS SUBGRADE SOIL CONDITIONS AND FOR LIGHT-, MEDIUM-, AND HEAVY-DUTY TRAFFIC

R-Value of Subgrade Soil	Calif. Traffic Index	Flexible Pavement Design Depth, in Inches: With Crushed Stone Base				With Standard CTB Base				With Heavy CTB Base			
		Asphalt Concrete Surface	Crushed Stone Base	Subbase	Total Depth	Asphalt Concrete Surface	CTB Base[a]	Subbase	Total Depth	Asphalt Concrete Surface	CTB Base[a]	Subbase	Total Depth
R 5	8.5	3½	8	15	26½	3	8-A	10	21	3	10-A	7	20
	10.0	4	10	18	32	4	10-A	11	25	4	10-A	10	24
	11.5	6	10	20	36	6	10-A	13	29	6	10-A	12	28
R 20	8.5	3½	8	11	22½	3	8-A	5	16	3	8-A	5	16
	10.0	4	10	12	26	4	10-A	5	19	4	10-A	5	19
	11.5	6	10	13	29	6	10-A	6	22	6	10-A	6	22
R 35	8.5	3½	8	6	17½	3	8-A	—	11	3	8-A	—	11
	10.0	4	10	6	20	4	10-A	—	14	4	5-A	5	14
	11.5	6	10	7	23	6	10-A	—	16	6	5-A	5	16
R 50	8.5	3½	9	—	12½	3	8-B	—	11	3	8-B	—	11
	10.0	4	10	—	14	4	10-A	—	14	4	10-A	—	14
	11.5	6	10	—	16	6	10-A	—	16	6	10-A	—	16
R 65	8.5	3½	8	—	11½	3	8 Cr. St.	—	11	3	8 Cr. St.	—	11
	10.0	4	10	—	14	4	10 Cr. St.	—	14	4	10 Cr. St.	—	14
	11.5	6	10	—	16	6	10 Cr. St.	—	16	6	10 Cr. St.	—	16
R 80	8.5	3½	8	—	11⅓	3	8 Cr. St.	—	11	3	8 Cr. St.	—	11
	10.0	4	10	—	14	4	10 Cr. St.	—	14	4	10 Cr. St.	—	14
	11.5	6	10	—	16	6	10 Cr. St.	—	16	6	10 Cr. St.	—	16

[a]The two types of cement/treated base used in this study consist of: (1) Type A with 3½ to 6 percent portland cement by weight of the dry aggregate. (2) Type B with 2½ to 4½ percent portland cement by weight of the dry aggregate. For subgrade soils with R-values of 65 and 80, a crushed stone base is used instead of a cement-treated base.

TABLE 3

SHOULDERS STRUCTURAL DESIGN SECTIONS FOR RIGID AND FLEXIBLE PAVEMENTS DESIGNED FOR VARIOUS SOIL CONDITIONS AND FOR LIGHT-, MEDIUM-, AND HEAVY-DUTY TRAFFIC

R-Value of Subgrade Soil	Calif. Traffic Index	Shoulder Design Depth, in Inches[a]: Minimum Depths Based on Design Formula			Depths Adopted for Rigid Pavements with Cement-Treated Base				Depths Adopted for Flexible Pavements with Standard CTB Base			
		Asphalt Concrete Surface	Base and Subbase	Total Depth	Asphalt Concrete Surface	Base—Crushed Stone	Subbase	Total Depth	Asphalt Concrete Surface	Base—Crushed Stone	Subbase	Total Depth
R 5	8.5	2	15	17	3-2	4	13	20	3-2	4	14	21
	10.0	3	18	20	4-2	4	15	23	4-2	4	17	25
	11.5	3	20	23	4-2	4	17	25	4-2	4	21	29
R 20	8.5	2	12	14	3-2	4	11	18	3-2	4	9	16
	10.0	3	13	16	4-2	4	13	21	4-2	4	11	19
	11.5	3	16	19	4-2	4	15	23	4-2	4	14	22
R 35	8.5	2	9	11	3-2	4	11	18	3-2	4	4	11
	10.0	3	10	13	4-2	4	11	19	4-2	4	6	14
	11.5	3	12	15	4-2	4	13	21	4-2	4	8	16
R 50	8.5	2	6	8	3-2	4	11	18	3-2	4	4	11
	10.0	3	7	10	4-2	4	11	19	4-2	4	6	14
	11.5	3	8	11	4-2	4	11	19	4-2	4	8	16
R 65	8.5	2	3	5	3-2	4	5	12	3-2	4	4	11
	10.0	3	3	6	4-2	4	5	13	4-2	4	6	14
	11.5	3	5	8	4-2	4	5	13	4-2	4	8	16
R 80	8.5	2	—	2	3-2	4	5	12	3-2	4	4	11
	10.0	3	—	3	4-2	4	5	13	4-2	4	6	14
	11.5	3	—	3	4-2	4	5	13	4-2	4	8	16

[a]The shoulder design adopted for both the rigid and flexible pavement types provides for a uniform depth of pavement and shoulder cross-section.

the flexible pavement sections instead of only one type of base used for the rigid pavement sections. It should be noted that for light-duty traffic a 3½-in. asphalt concrete pavement thickness was used and for heavy-duty traffic a 6-in. thickness was used. The maximum total depth for the flexible pavement design was 36 in. as compared with a 25-in. depth for the corresponding rigid pavement design section. The minimum total depth for the flexible pavement design was 11 in. as compared with a minimum depth of 12 in. for the rigid pavement design. The above minimum depths of pavement apply only to well-drained soils with high R-values where a subbase is not required for either flexible or rigid pavements.

The shoulder design sections for both the rigid and flexible pavement cross-sections are given in Table 3. The shoulder design in California is based on a traffic design load of 1 percent of the EWL but with a TI of not less than 4.5 or more than 7.5. In

TABLE 4

UNIT CONTRACT PRICES FOR THE CONSTRUCTION OF PORTLAND CEMENT CONCRETE PAVEMENTS ON 37 CALIFORNIA STATE HIGHWAY PROJECTS IN 1958 AND ON 44 PROJECTS IN 1960

Pavement Item	Contract Price Rating[a]	Unit Price ($ per sq yd)	
		1958	1960
Concrete paving, including tie bolts:			
8-in. thickness	Low	3.00	2.80
	High	4.70	3.70
	Average	3.52	3.20
9-in. thickness	Low	3.40	3.30
	High	4.80	4.50
	Average	3.97	3.83
Base course, including curing seal:			
Cement-treated (Type A), 4-in. thick.	Low	0.50	0.65
	High	1.00	0.90
	Average	0.77	0.79
Cement-treated (Type B), 4-in. thick.	Low	-	0.45
	High	-	0.75
	Average	-	0.60
Subbase:			
Imported borrow, per inch of thickness	Low	0.03	0.03
	High	0.12	0.12
	Average	0.07	0.06

[a]The contract price rating adopted for this study was established on the following basis:
Low—represents the 10 percentile value.
High—represents the 90 percentile value.
Average—represents the arithmetical mean.

TABLE 5

UNIT CONTRACT PRICES FOR THE CONSTRUCTION OF ASPHALT CONCRETE PAVEMENTS ON 63 STATE HIGHWAY PROJECTS IN CALIFORNIA IN 1958 AND ON 111 PROJECTS IN 1960

Pavement Item	Contract Price Rating[a]	Unit Price ($ per sq yd)	
		1958	1960
Asphalt concrete surface:			
1-in. thickness	Low	-	0.33
	High	-	0.49
	Average	-	0.40
2-in. thickness	Low	0.60	0.61
	High	0.96	0.89
	Average	0.72	0.73
3-in. thickness	Low	0.75	0.78
	High	1.12	1.23
	Average	0.92	1.05
4-in. thickness	Low	1.10	1.15
	High	1.55	1.69
	Average	1.25	1.34
6-in. thickness	Low	-	1.71
	High	-	2.49
	Average	-	1.98
Prime coat	Low	0.03	0.03
	High	0.05	0.09
	Average	0.04	0.06
Base course:			
Cement-treated—Type A per inch of thickness	Low	0.16	0.16
	High	0.23	0.24
	Average	0.20	0.19
Cement-treated—Type B per inch of thickness	Low	0.13	0.12
	High	0.22	0.20
	Average	0.17	0.17
Crushed stone base per inch of thickness	Low	0.06	0.07
	High	0.13	0.14
	Average	0.09	0.10
Subbase:			
Imported borrow, per inch of thickness	Low	0.03	0.03
	High	0.11	0.12
	Average	0.06	0.06

[a]The contract price rating adopted for this study was established on the following basis: low—represents the 10 percentile value, high—represents the 90 percentile value, and average—represents the arithmetical mean.

Table 3, the minimum depths of shoulder based on the above design criteria are given. The shoulder design adopted for both the rigid and flexible pavement types, however, provided for a uniform depth of pavement and shoulder which in all cases was greater than the minimum depth based on the traffic requirements. The use of a uniform depth of pavement and shoulder instead of a trench section is a design procedure widely used today in California and in many other states. For poor subgrade soil types, it increased the required depth of shoulders for flexible pavements by a greater amount than the depth of shoulders required for rigid pavements. For subgrade soils with R-values of 35 and 50, the required depths of shoulder for flexible pavements in this study were slightly lower than for rigid pavements. For R-values of 65 and 80, the shoulder depths for flexible pavements were the same or slightly higher than for rigid pavements.

The initial construction costs for the pavements and shoulders were computed using cost data obtained from the 1958 and 1960 annual reports of the "Construction Costs of Portland Cement Concrete Pavements and of Asphalt Concrete Pavements on Highways in California" prepared by the Pacific Coast Division of The Asphalt Institute (9). The accuracy of the unit cost data in these reports was verified by the authors and by the design engineers of the California Division of Highways by comparing the unit costs in these reports with the original records of contract bid prices and with the cost data in the California Division of Highways Contract Item Data Report for 1960 (10).

The unit contract prices for the construction of portland cement concrete pavements on 37 California state highway projects in 1958 and on 44 projects in 1960 are given in Table 4 and the corresponding costs for asphalt concrete pavements on 63 projects in 1958 and for 111 projects in 1960 are given in Table 5. For this study the unit costs for 155 paving projects for which contracts were awarded in California in 1960 were used as given in Tables 4 and 5. The unit prices for each pavement item for which

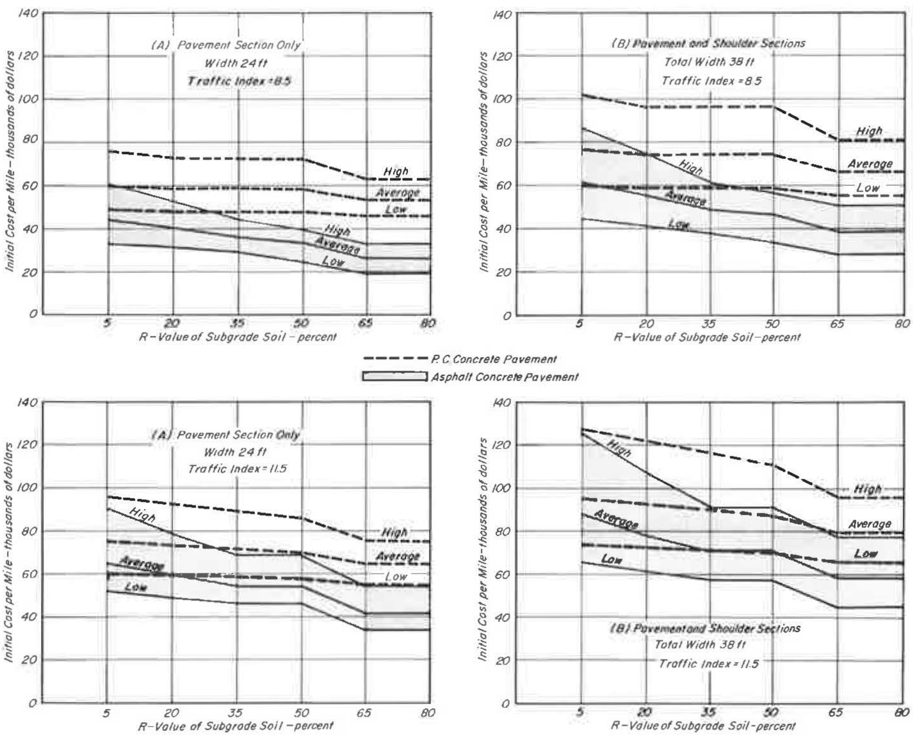

Figure 2. Initial construction costs per mile for (a) 2-lane concrete and asphalt pavements and (b) pavements and shoulders, designed for six subgrade soil types, for light-duty traffic (TI = 8.5) and heavy-duty traffic (TI = 11.5).

TABLE 6

INITIAL CONSTRUCTION COSTS PER MILE FOR 2-LANE PORTLAND CEMENT CONCRETE PAVEMENT AND SHOULDERS[a]

Design Section					Initial Construction Costs per Mile			
No.	R-Value of Subgrade Soil	Traffic Index	Total Pvmt. Depth (in.)	Contract Price Rating	Cost of Pavement per Mile ($)	Cost of Shoulders per Mile ($)	Ratio Pvmt. vs Shoulder Costs per Mile	Total Cost, Pavement and Shoulders per Mile ($)
1	R 5	8.5	20	Low	49,140	11,250	4.4	60,390
				High	76,170	26,120	2.9	102,290
				Average	60,260	17,000	3.5	77,260
2		10.0	23	Low	59,840	12,400	4.8	72,240
				High	92,930	29,490	3.2	122,420
				Average	73,500	19,300	3.8	92,800
3		11.5	25	Low	60,680	12,890	4.9	73,570
				High	96,310	31,460	3.1	127,770
				Average	75,190	20,290	3.7	95,480
7	R 35	8.5	18	Low	48,290	10,760	4.6	59,050
				High	72,800	24,150	3.0	96,950
				Average	58,570	16,020	3.7	74,590
8		10.0	19	Low	58,150	11,420	5.1	69,570
				High	86,170	25,540	3.5	111,710
				Average	70,120	17,330	4.0	87,450
9		11.5	21	Low	59,000	11,910	5.0	70,910
				High	89,550	27,510	3.3	117,060
				Average	71,810	18,320	3.9	90,130
10	R 50	8.5	18	Low	48,290	10,760	4.5	59,050
				High	72,800	24,150	3.0	96,950
				Average	58,570	16,020	3.7	74,590
11		10.0	19	Low	58,150	11,420	5.1	69,570
				High	86,170	25,540	3.4	111,710
				Average	70,120	17,330	3.5	87,450
12		11.5	19	Low	58,150	11,420	5.1	69,570
				High	86,170	25,540	3.4	111,710
				Average	70,120	17,330	4.0	87,450
13	R 65	8.5	12	Low	45,760	9,280	4.9	55,040
				High	62,660	18,230	3.4	80,890
				Average	53,500	13,060	4.1	66,560
14		10.0	13	Low	55,620	9,940	5.6	65,560
				High	76,030	19,630	3.9	95,660
				Average	65,050	14,370	4.5	79,420
15		11.5	13	Low	55,620	9,940	5.6	65,560
				High	76,030	19,630	3.9	95,660
				Average	65,050	14,370	4.5	79,420

[a]Based on the contract prices for 44 state highway paving projects in 1960.

TABLE 7

INITIAL CONSTRUCTION COSTS PER MILE FOR 2-LANE ASPHALT CONCRETE PAVEMENT AND SHOULDERS WITH CRUSHED STONE BASE[a]

Design Section					Initial Construction Costs per Mile			
No.	R-Value of Subgrade Soil	Traffic Index	Total Pvmt. Depth (in.)	Contract Price Rating	Cost of Pavement per Mile ($)	Cost of Shoulders per Mile ($)	Cost of Pvmt. vs Shoulder Costs per Mile	Total Cost, Pavement and Shoulders per Mile ($)
1	R 5	8.5	26½	Low	27,680	12,890	2.2	40,770
				High	61,670	32,520	1.9	94,190
				Average	40,830	20,200	2.0	61,030
2		10.0	32	Low	33,650	14,620	2.3	48,270
				High	73,920	38,360	1.9	112,280
				Average	48,150	23,740	2.0	71,890
3		11.5	36	Low	42,380	15,610	2.7	57,990
				High	88,560	42,300	2.1	130,860
				Average	58,850	25,710	2.3	84,560
7	R 35	8.5	17½	Low	24,080	10,680	2.3	34,760
				High	46,460	23,650	2.0	70,110
				Average	33,230	15,770	2.1	49,000
8		10.0	20	Low	28,580	11,660	2.5	40,240
				High	53,640	26,530	2.0	80,170
				Average	38,020	17,820	2.1	55,840
9		11.5	23	Low	36,890	11,580	3.2	48,470
				High	66,600	29,490	2.3	96,090
				Average	47,870	19,300	2.5	67,170
10	R 50	8.5	12½	Low	22,530	9,450	2.4	31,980
				High	38,300	18,730	2.0	57,030
				Average	29,570	13,310	2.2	42,880
11		10.0	14	Low	26,050	10,180	2.6	36,230
				High	43,510	20,620	2.1	64,130
				Average	32,950	14,870	2.2	47,820
12		11.5	16	Low	33,930	10,680	3.2	44,610
				High	54,770	22,590	2.4	77,360
				Average	41,960	15,850	2.6	57,810
13	R 65	8.5	11½	Low	21,540	9,200	2.3	30,740
				High	36,330	17,740	2.1	54,070
				Average	28,160	12,810	2.2	40,970
14		10.0	14	Low	26,050	10,180	2.6	36,230
				High	43,510	20,620	2.1	64,130
				Average	32,950	14,870	2.2	47,820
15		11.5	16	Low	33,930	10,680	3.2	44,610
				High	54,770	22,590	2.4	77,360
				Average	41,960	15,850	2.6	57,810

[a]Based on the contract prices for 111 state highway paving projects in 1960.

TABLE 8

INITIAL CONSTRUCTION COSTS PER MILE FOR 2-LANE ASPHALT CONCRETE PAVEMENT AND SHOULDERS WITH STANDARD CEMENT TREATED BASE[a]

Design Section					Initial Construction Costs per Mile			
No.	R-Value of Subgrade Soil	Traffic Index	Total Pvmt. Depth (in.)	Contract Price Rating	Cost of Pavement per Mile ($)	Cost of Shoulders per Mile ($)	Ratio Pvmt. vs Shoulder Costs per Mile	Total Cost, Pavement and Shoulders per Mile ($)
1	R 5	8.5	21	Low	33,230	11,500	2.8	44,730
				High	61,250	26,280	2.3	87,530
				Average	44,630	17,490	2.6	62,120
2		10.0	25	Low	43,370	12,890	3.4	56,260
				High	76,170	32,610	2.3	108,780
				Average	54,910	20,860	2.6	75,770
3		11.5	29	Low	52,100	13,880	3.8	65,980
				High	90,820	35,400	2.6	126,220
				Average	65,610	22,260	3.0	87,870
7	R 35	8.5	11	Low	29,000	9,030	3.2	38,030
				High	44,350	17,250	2.6	61,600
				Average	36,190	12,520	2.9	48,760
8		10.0	14	Low	38,720	10,180	3.8	48,900
				High	57,590	20,620	2.8	78,210
				Average	45,620	14,870	3.1	60,490
9		11.5	16	Low	46,600	10,680	4.4	57,280
				High	68,850	22,590	3.1	91,440
				Average	54,630	15,850	3.5	70,480
10	R 50	8.5	11	Low	24,500	9,030	2.7	33,530
				High	30,860	17,350	2.3	57,100
				Average	33,930	12,520	2.7	46,500
11		10.0	14	Low	38,720	10,180	3.8	48,900
				High	57,590	20,620	2.8	78,210
				Average	45,620	14,870	3.1	60,490
12		11.5	16	Low	46,600	10,680	4.4	57,280
				High	68,850	22,590	3.0	91,440
				Average	54,630	15,850	3.4	70,480
13	R 65[b]	8.5	11	Low	18,870[b]	9,030	2.1	27,900[b]
				High	33,090	17,250	1.9	50,340
				Average	26,050	12,570	2.1	38,620
14		10.0	14	Low	26,050[b]	10,180	2.6	36,230[b]
				High	43,510	20,620	2.1	64,130
				Average	32,950	14,870	2.2	47,820
15		11.5	16	Low	33,930[b]	10,680	3.2	44,610[b]
				High	54,770	22,590	2.4	77,360
				Average	41,960	15,850	2.6	57,810

[a]Based on the contract prices for 111 state highway paving projects in 1960.
[b]For subgrade soils with R-values of 65, a crushed stone base is used instead of a cement-treated base. Hence, the cost of the pavement portion of the roadway for the R 65 soils was computed using the unit prices for crushed stone base instead of cement-treated base construction.

TABLE 9

INITIAL CONSTRUCTION COSTS PER MILE FOR 2-LANE ASPHALT CONCRETE PAVEMENT AND SHOULDERS WITH HEAVY CEMENT-TREATED BASE[a]

Design Section					Initial Construction Costs per Mile			
No.	R-Value of Subgrade Soil	Traffic Index	Total Pvmt. Depth (in.)	Contract Price Rating	Cost of Pavement per Mile ($)	Cost of Shoulders per Mile ($)	Ratio Pvmt. vs Shoulder Costs per Mile	Total Cost, Pavement and Shoulders per Mile ($)
1	R 5	8.5	20	Low	36,470	11,250	3.2	47,720
				High	62,940	26,120	2.4	89,060
				Average	47,450	17,000	2.8	64,450
2		10.0	24	Low	42,940	12,650	3.4	55,590
				High	74,480	30,470	2.4	104,950
				Average	54,070	19,790	2.7	73,860
3		11.5	28	Low	51,670	13,640	3.8	65,310
				High	80,130	34,410	2.6	123,540
				Average	64,770	21,770	3.0	86,540
7	R 35	8.5	11	Low	29,000	9,030	3.2	38,030
				High	44,350	17,250	2.6	61,600
				Average	36,190	12,570	2.9	48,760
8		10.0	14	Low	35,900	10,180	3.5	46,080
				High	54,770	20,620	2.7	75,390
				Average	44,210	14,870	3.0	59,080
9		11.5	16	Low	43,790	10,680	4.1	54,470
				High	66,040	22,590	2.9	88,630
				Average	53,220	15,850	3.4	69,030
10	R 50	8.5	11	Low	24,500	9,030	2.7	33,530
				High	39,850	17,250	2.3	57,100
				Average	33,930	12,570	2.7	46,500
11		10.0	14	Low	38,720	10,180	3.8	48,900
				High	57,590	20,620	2.8	78,210
				Average	45,620	14,870	3.1	60,490
12		11.5	16	Low	46,600	10,680	4.4	57,280
				High	68,850	22,590	3.0	91,440
				Average	54,630	15,850	3.4	70,480
13	R 65[b]	8.5	11	Low	18,870[b]	9,030	2.1	27,900[b]
				High	33,090	17,250	1.9	50,340
				Average	26,050	12,570	2.1	38,620
14		10.0	14	Low	26,050[b]	10,180	2.6	36,230[b]
				High	43,510	20,620	2.1	64,130
				Average	32,950	14,870	2.2	47,820
15		11.5	16	Low	33,930[b]	10,680	3.2	44,610[b]
				High	54,770	22,590	2.4	77,360
				Average	41,960	15,850	2.6	57,810

[a]Based on the contract prices for 111 state highway paving projects in 1960.
[b]For subgrade soils with R-values of 65, a crushed stone base is used instead of a cement-treated base. Hence, the cost of the pavement portion of the roadway for the R 65 soils was computed using the unit prices for crushed stone base instead of cement-treated base construction.

bids were submitted, such as for the portland cement concrete and asphalt concrete surfaces, for the various types of base courses, and for the subbases were reduced to a common unit adopted for this study: the unit price in dollars per sq yd per inch of thickness or for a given design thickness (i.e., for an 8-in. portland cement concrete slab or a 4-in. CTB). To indicate the wide range in the contract prices for projects in all parts of California, a price rating method was adopted in which low represents the 10 percentile value and high the 90 percentile value for all contract prices of similar items for the 155 paving projects. Average represents the arithmetical mean for all prices of similar items.

The unit cost data given in Tables 4 and 5 indicate a surprising uniformity in the contract prices for the same pavement items in 1958 and 1960. It is significant that certain recent improvements in the construction of portland cement concrete pavements, such as the use of slip-form pavers and of paving over 2-lane widths instead of 1-lane widths, appear to have brought about the decrease in unit prices for 1960 given in Table 4. The data in Table 5 indicate a slight increase in the unit prices for asphalt concrete pavements over the 2-yr period from 1958 to 1960.

The initial construction costs of the rigid and flexible pavements, of the shoulders, and of the total roadway section were computed in terms of a 2-lane roadway one mile in length for one direction of travel. The computed costs are shown in Figure 2 and in Tables 6, 7, 8, and 9. The costs for the six subgrade soils shown in Figure 2, starting with the very high costs for pavements designed for the very poor R 5 soil to the low costs for pavements designed for the excellent R 80 soils, show a uniform pattern and trend in costs which may be attributed to the type of subgrade soil. Since the trend in costs is clearly indicated in Figure 2, the values for the initial construction costs are shown only for the R 5, R 35 and R 65 soils in Tables 6 to 9, thereby eliminating the duplication of costs for certain soil types and reducing the size and complexity of the tables.

It should be noted in Figure 2 and in Tables 6 to 9 that by including the cost of shoulders in the comparison of initial construction costs of rigid and flexible pavements, a variable cost factor is introduced which reduces the cost differential between rigid and flexible pavements for many of the design sections, especially for the sections with the greater pavement depth. For rigid pavements, the ratio of pavement to shoulder costs varies from 3.0 to 5.6, whereas for flexible pavements this ratio varies from 2.0 to 4.4. A major reason for the higher costs of shoulders for flexible pavements, where this occurs, is the greater depth of pavement required for these sections which in turn require a greater shoulder depth in accordance with the uniform pavement and shoulder depth design procedure adopted for this study.

Table 6 gives the initial costs for the portland cement concrete pavement sections, the shoulder sections, and the combined concrete pavement and shoulder sections. In California only one type of base, the 4-in. CTB, is normally used in the construction of concrete pavements, and therefore all of the initial costs for the portland cement concrete pavement sections used in this study are given in one table. However, in computing the construction costs of asphalt concrete pavements, three types of bases—crushed stone, standard CTB, and heavy CTB—were used, and accordingly the initial costs for the asphalt concrete pavement and shoulder sections with each of these three bases are given in Tables 7, 8 and 9.

A significant feature of the initial costs given in Tables 6 to 9 is the wide range in the initial costs for both the rigid and flexible pavement construction required to satisfy the structural design requirements for the various soil types and traffic loads. For many of the sections, especially for the sections with the greatest pavement depths designed for poor subgrade soil conditions, the spread in the initial costs from high to low based on the contract bid prices in 1960 was greater than the spread in costs due to the variations in pavement design sections. The wide range in the construction costs per 2-lane mile for pavement and shoulders based on 1960 prices is indicated in the following comparison of the costs for the maximum depth of pavement required for heavy-duty traffic and a very poor R 5 subgrade soil and the minimum depth of pavement required for light-duty traffic and an excellent R 80 subgrade soil:

Pavement Items and Depth	Soil	Traffic	Pavement Depth (in.)	Cost per Mile ($)	
				High	Low
Portland cement concrete (9 in.) with cement-treated base (CTB) (4 in.)	R 5	TI = 11.5	25	$127,800	$73,600
Asphalt concrete (6 in.) with crushed stone base					
(10 in.), standard CTB	R 5	TI = 11.5	36	130,900	58,000
(10 in.), heavy CTB	R 5	TI = 11.5	29	126,200	66,000
(10 in.)	R 5	TI = 11.5	28	123,500	65,300
Portland cement concrete (8 in.) with CTB (4 in.)	R 80	TI = 8.5	12	$ 88,900	$ 55,000
Asphalt concrete (3 in.) with crushed stone base (8 in.)	R 80	TI = 8.5	11	50,300	27,900

These data show that the construction costs of rigid and flexible pavements designed for heavy-duty traffic and for poor soil conditions are all within the same price bracket but that the costs of the rigid pavement designed for light-duty traffic and for excellent soil conditions are almost double the costs of flexible pavements designed for these same conditions.

It is interesting to note in the foregoing comparision of initial costs for asphalt concrete pavements with three types of base construction and in the complete listing of these costs given in Tables 7, 8, and 9, that there is a marked difference in the initial cost of flexible pavements depending on the type of base course used. When only the pavement sections are considered, the pavements with the crushed stone base were generally found to have the lowest initial costs, but when the costs were computed for the full width of roadway including the shoulders, the standard CTB yielded the lowest cost, except for the sections designed for very poor soils and for heavy-duty traffic where the heavy CTB construction was lowest. These data clearly indicate that cost comparisions should be made for each type of base construction since the data show that under certain specific traffic and soil conditions each type of base may provide a definite cost advantage which can and should be evaluated.

It is readily apparent from an examination of the initial construction cost data given in Figure 2 and in Tables 6 to 9, that with pavement depths ranging from 11 to 36 in., there should be a corresponding spread in the initial construction costs. The reason for the wide spread in actual construction costs for the same pavement design section, however, is not so apparent and is rather difficult to explain. Indeed, there are many factors which influence the contract price for the various items in the construction of pavements in a state as large as California with such a wide range in climate, availability, and quality of paving materials, and in many other factors which influence pavement costs. The unit prices for various paving items given in Tables 4 and 5 indicate a much wider spread in the cost of aggregates used in base and subbase construction than in the cost of asphalt concrete or portland cement concrete pavement surfacing. The size and location of the paving projects, the access to paving plants and/or the cost of moving paving plants from one job to another, the competition in bidding on various paving projects, the supply of labor and materials, unbalanced bidding, traffic conflicts, controls and detour requirements, and the climatic or weather conditions during construction are factors which contributed to the wide variations in the unit bid prices submitted by various contractors for the various items on paving projects for which contracts were awarded in California in 1960.

It should be evident on the basis of the foregoing discussion that pavement cost comparisons should be made on a project-by-project basis using the structural design, traffic, and cost data which apply to the particular area and project under consideration instead of using statewide cost data of the type used in this study. The use of statewide cost data in this study resulted in the wide spread in the initial costs for both rigid and flexible pavements shown in Figure 2.

Resurfacing Costs

The resurfacing thickness requirements and costs for both the rigid and flexible pavement types were assumed to be independent of the structural design sections for each pavement type. Although a greater thickness was used for the first resurfacing of the portland cement concrete pavements than for the asphalt concrete pavements, the same resurfacing thickness was used for each pavement type for each of the 18 design sections.

The California Division of Highways has been engaged in extensive resurfacing programs for many years. Asphalt concrete overlays of various thicknesses have been used to resurface both rigid and flexible pavements. In 1960 about 70 percent of the total mileage or resurfacing of flexible pavements consisted of an asphalt concrete overlay with a uniform thickness of 1 in. For the remaining mileage the thickness was increased to 1 ½ in. and 2 in. For rigid pavements an asphalt concrete overlay with an average thickness of 3 in. was used. The 3-in. thickness of asphalt concrete overlay has been widely used in many states for resurfacing portland cement concrete pavements and was adopted as the thickness for resurfacing the rigid pavements in this study. For flexible pavements an average thickness of 1 ½ in. was used for resurfacing the traveled way portion of the roadway.

For resurfacing the shoulders a tapered section was adopted for both the rigid and flexible pavement sections. For the rigid pavements, a thickness of 3 in. at the edge of the traveled way was tapered to 1 in. at the outer edge of the shoulder for the first resurfacing. Where a second resurfacing was used on rigid pavements, the thickness

TABLE 10

RESURFACING COSTS PER MILE FOR 2-LANE WIDTH OF RIGID PAVEMENT AND FOR SHOULDERS[a]

Traffic Index	1960 Contracts: Price Rating	1960 Contracts: Costs per Mile ($)	Costs at End of 18th Yr (2% price-trend factor = 1.4282) ($)	Costs for Engg. (10%) and Suppl. Work (6%) ($)	Traffic Delay and Accident Costs ($)	Total Resur. Costs at End of 18th Yr ($)	Present Worth Resur. Costs: Int. at 3% ($)	Present Worth Resur. Costs: Int. at 6% ($)
(a) Pavement Resurfacing Costs per Mile								
8.5	Low	10,980	15,680	2,510	20	18,210	10,700	6,380
	High	17,320	24,740	8,960	20	28,720	16,870	10,060
	Avg.	14,780	21,110	3,380	20	24,510	14,400	8,590
10.0	Low	10,980	15,680	2,510	100	18,290	10,740	6,410
	High	17,320	24,740	8,960	100	28,800	16,910	10,090
	Avg.	14,780	21,110	3,380	100	24,590	14,440	8,610
11.5	Low	10,980	15,680	2,510	300	18,490	10,860	6,480
	High	17,320	24,740	8,960	300	29,000	17,030	10,160
	Avg.	14,780	21,110	3,380	300	24,790	14,670	8,680
(b) Shoulder Resurfacing Costs per Mile								
8.5	Low	5,010	7,160	1,150	20	8,330	4,890	2,920
	High	7,310	10,440	1,670	20	12,130	7,130	4,250
	Avg.	6,000	8,570	1,370	20	9,960	5,850	3,490
10.0	Low	5,010	7,160	1,150	80	8,390	4,930	2,940
	High	7,310	10,440	1,670	80	12,190	7,160	4,270
	Avg.	6,000	8,570	1,370	80	10,020	5,890	3,510
11.5	Low	5,010	7,160	1,150	240	8,550	5,020	3,000
	High	7,310	10,440	1,670	240	12,350	7,250	4,330
	Avg.	6,000	8,570	1,370	240	10,180	5,980	3,570

[a]Service life of pavement, 18 yr; life of asphalt concrete resurfacing, 13 yr; analysis period, 26 yr; thickness of asphalt concrete resurfacing for pavement, 3 in., and for shoulders, 2 in.

TABLE 11

RESURFACING COSTS PER MILE FOR 2-LANE WIDTH OF RIGID PAVEMENT AND FOR SHOULDERS[a]

Traffic Index	1960 Contracts: Price Rating	1960 Contracts: Costs per Mile ($)	Costs at End of 26th Yr (2% price-trend factor = 1.6734) ($)	Costs for Engg. (10%) and Suppl. Work (6%) ($)	Traffic Delay and Accident Costs ($)	Total Resur. Costs at End of 26th Yr ($)	Present Worth Resur. Costs: Int. at 3% ($)	Present Worth Resur. Costs: Int. at 6% ($)
(a) Pavement Resurfacing Costs per Mile								
8.5	Low	10,980	17,970	2,880	20	20,870	9,680	4,590
	High	17,320	28,350	4,540	20	32,910	15,260	7,230
	Avg.	14,780	24,190	3,870	20	28,080	13,020	6,170
10.0	Low	10,980	17,970	2,880	100	20,950	9,710	4,600
	High	17,320	28,350	4,540	100	32,990	15,300	7,250
	Avg.	14,780	24,190	3,870	100	28,160	13,060	6,190
11.5	Low	10,980	17,970	2,880	300	21,150	9,810	4,650
	High	17,320	28,350	4,540	300	33,190	15,390	7,300
	Avg.	14,780	24,190	3,870	300	28,360	13,150	6,230
(b) Shoulder Resurfacing Costs per Mile								
8.5	Low	5,010	8,380	1,340	20	9,740	4,520	2,140
	High	7,310	12,230	1,940	20	14,190	6,580	3,120
	Avg.	6,000	10,040	1,610	20	11,670	5,410	2,570
10.0	Low	5,010	8,380	1,340	80	9,800	4,540	2,150
	High	7,310	12,230	1,940	80	14,250	6,610	3,130
	Avg.	6,000	10,040	1,610	80	11,730	5,440	2,580
11.5	Low	5,010	8,380	1,340	240	9,960	4,620	2,190
	High	7,310	12,230	1,940	240	14,410	6,680	3,170
	Avg.	6,000	10,040	1,610	240	11,890	5,510	2,610

[a]Service life of pavement, 26 yr; life of asphalt concrete resurfacing, 13 yr; analysis period, 39 yr; thickness of asphalt concrete resurfacing for pavements, 3 in., and for shoulders, 2 in.

TABLE 12

RESURFACING COSTS PER MILE FOR 2-LANE WIDTH OF FLEXIBLE PAVEMENT AND FOR SHOULDERS[a]

Traffic Index	1960 Contracts: Price Rating	1960 Contracts: Costs per Mile ($)	Costs at End of 13th Yr (2% price-trend factor = 1.2936) ($)	Costs for Engg. (10%) and Suppl. Work (6%) ($)	Traffic Delay and Accident Costs ($)	Total Resur. Costs at End of 13th Yr ($)	Present Worth Resur. Costs: Int. at 3% ($)	Present Worth Resur. Costs: Int. at 6% ($)
(a) Pavement Resurfacing Costs per Mile								
8.5	Low	6,760	8,750	1,400	10	10,160	6,920	4,760
	High	9,720	12,570	2,010	10	14,590	9,940	6,840
	Avg.	8,030	10,390	1,660	10	12,060	8,210	5,650
10.0	Low	6,760	8,750	1,400	70	10,220	6,960	4,790
	High	9,720	12,570	2,010	70	14,650	9,980	6,870
	Avg.	8,030	10,390	1,660	70	12,120	8,250	5,680
11.5	Low	6,760	8,750	1,400	200	10,350	7,050	4,850
	High	9,720	12,570	2,010	200	14,780	10,070	6,930
	Avg.	8,030	10,390	1,660	200	12,250	8,340	5,740
(b) Shoulder Resurfacing Costs per Mile								
8.5	Low	3,290	4,260	680	10	4,950	3,370	2,320
	High	4,850	6,270	1,000	10	7,280	4,960	3,410
	Avg.	3,940	5,100	820	10	5,930	4,040	2,780
10.0	Low	3,290	4,260	680	50	4,990	3,400	2,340
	High	4,850	6,270	1,000	50	7,320	4,980	3,430
	Avg.	3,940	5,100	820	50	5,970	4,070	2,800
11.5	Low	3,290	4,260	680	150	5,090	3,470	2,390
	High	4,850	6,270	1,000	150	7,420	5,050	3,480
	Avg.	3,940	5,100	820	150	6,050	4,120	2,840

[a]Service life of pavement, 13 yr; life of resurfacing, 13 yr; analysis period, 26 yr; thickness of asphalt concrete resurfacing for pavement, $1\frac{1}{2}$ in., and for shoulders, $1\frac{1}{4}$ in.

TABLE 13

RESURFACING COSTS PER MILE FOR 2-LANE WIDTH (24 Ft) OF FLEXIBLE PAVEMENT[a]

Traffic Index	1960 Contracts: Price Rating	1960 Contracts: Costs per Mile ($)	Costs at End of 18th Yr (2% price-trend factor = 1.4282) ($)	Costs at End of 31st Yr (2% price-trend factor = 1.8476) ($)	Costs for Engg. (10%) and Suppl. Work (6%) ($)	Traffic Delay and Accident Costs ($)	Total Resur. Costs at End of 18th Yr ($)	Total Resur. Costs at End of 31st Yr ($)	Present Worth ($): First Resur. Costs: Int. at 3%	Present Worth ($): First Resur. Costs: Int. at 6%	Present Worth ($): Second Resur. Costs: Int. at 3%	Present Worth ($): Second Resur. Costs: Int. at 6%
(a) First Pavement Resurfacing Cost per Mile												
8.5	Low	6,760	9,650		1,540	10	11,200		6,580	3,920		
	High	9,720	13,880		2,220	10	16,110		9,460	5,640		
	Avg.	8,030	11,470		1,840	10	13,320		7,820	4,670		
10.0	Low	6,760	9,650		1,540	70	11,260		6,610	3,940		
	High	9,720	13,880		2,220	70	16,170		9,500	5,660		
	Avg.	8,030	11,470		1,840	70	13,380		7,860	4,690		
11.5	Low	6,760	9,650		1,540	200	11,390		6,690	3,990		
	High	9,720	13,880		2,220	200	16,300		9,570	5,710		
	Avg.	8,030	11,470		1,840	200	13,510		7,940	4,730		
(b) Second Pavement Resurfacing Cost per Mile												
8.5	Low	6,760		12,490	2,000	10		14,500			5,800	2,380
	High	9,720		17,960	2,870	10		20,840			8,340	3,420
	Avg.	8,030		14,840	2,370	10		17,220			6,890	2,830
10.0	Low	6,760		12,490	2,000	70		14,560			5,820	2,390
	High	9,720		17,960	2,870	70		20,900			8,360	3,430
	Avg.	8,030		14,840	2,370	70		17,280			6,910	2,840
11.5	Low	6,760		12,490	2,000	200		14,690			5,880	2,410
	High	9,720		17,960	2,870	200		21,030			8,410	3,460
	Avg.	8,030		14,840	2,370	200		17,410			6,960	2,860

[a]Service life of pavement, 18 yr; life of resurfacings, 13 yr; analysis period, 39 yr; thickness of asphalt concrete resurfacings, $1\frac{1}{2}$ in.

TABLE 14

RESURFACING COSTS PER MILE FOR SHOULDERS FOR 2-LANE FLEXIBLE PAVEMENT[a]

Traffic Index	1960 Contracts		Costs at End of 18th Yr (2% price-trend factor = 1.4282) ($)	Costs at End of 31st Yr (2% price-trend factor = 1.8476) ($)	Costs for Engg. (10%) and Suppl. Work (6%) ($)	Traffic Delay and Accident Costs ($)	Total Resur. Costs at End of 18th Yr ($)	Total Resur. Costs at End of 31st Yr ($)	Present Worth ($)			
									First Resur. Costs		Second Resur. Costs	
	Price Rating	Costs per Mile ($)							Int. at 3%	Int. at 6%	Int. at 3%	Int. at 6%
(a) First Shoulder Resurfacing Costs per Mile												
8.5	Low	3,290	4,700		530	10	5,240		3,080	1,840		
	High	4,850	6,930		780	10	7,720		4,530	2,700		
	Avg.	3,940	5,630		630	10	6,270		3,680	2,200		
10.0	Low	3,290	4,700		530	50	5,280		3,100	1,850		
	High	4,850	6,930		780	50	7,760		4,560	2,720		
	Avg.	3,940	5,630		630	50	6,310		3,710	2,210		
11.5	Low	3,290	4,700		530	150	5,380		3,160	1,880		
	High	4,850	6,930		780	150	7,860		4,620	2,750		
	Avg.	3,940	5,630		630	150	6,410		3,770	2,250		
(b) Second Shoulder Resurfacing Costs per Mile												
8.5	Low	3,290		6,080	970	10	7,060	7,060			2,820	1,160
	High	4,850		8,960	1,430	10	10,400	10,400			4,160	1,710
	Avg.	3,940		7,280	1,160	10		8,450			3,380	1,390
10.0	Low	3,290		6,080	970	50		7,100			2,840	1,170
	High	4,850		8,960	1,430	50		10,440			4,180	1,720
	Avg.	3,940		7,280	1,160	50		8,490			3,400	1,390
11.5	Low	3,290		6,080	970	150		7,200			2,880	1,180
	High	4,850		8,960	1,430	150		10,540			4,220	1,730
	Avg.	3,940		7,280	1,160	150		8,590			3,440	1,410

[a]Service life of pavement, 18 yr; life of asphalt concrete resurfacings, 13 yr; analysis period, 39 yr; average thickness of asphalt concrete resurfacings, $1\frac{1}{4}$ in.

for both the traveled way portion and the shoulder portion was the same as the thickness adopted for the second resurfacing of flexible pavements and shoulders.

For resurfacing the shoulders of flexible pavements, a thickness of $1\frac{1}{2}$ in. was used at the edge of the traveled way which was tapered to a 1-in. thickness at the outer edge of the shoulder for the first resurfacing. Where a second resurfacing of flexible pavements was required, the thickness of both the traveled way portion and the shoulder portion was the same as the thickness adopted for the first resurfacing of flexible pavements.

The construction costs for resurfacing both pavement types were computed in terms of the same 1960 unit contract prices which were used to compute the initial asphalt concrete paving costs. However, to determine the total cost of resurfacing, the three new resurfacing cost items adopted by the California Division of Highways in 1963 mentioned earlier in this paper were incorporated in this study. Thus, as is indicated in Tables 10 to 14, the total resurfacing costs for this study were computed on the basis of (a) the cost per mile for the given thickness of resurfacing using the 1960 unit prices for asphalt concrete pavement construction, (b) the increased cost for future resurfacing resulting from the application of a 2 percent compound interest price trend factor, (c) the increased cost for future resurfacing resulting from a 10 percent charge for preliminary and construction engineering work and from a 6 percent charge for supplemental work made necessary by the resurfacing, and (d) the cost of traffic delay and traffic accidents resulting from resurfacing operations. The increased costs for preliminary and construction engineering and for supplemental work were expressed as a percent of the future resurfacing cost. It should be noted in Tables 10 to 14 that all future resurfacing costs were converted to present worth costs by the use of 3 percent and 6 percent compound interest rates.

All of the values used in computing the resurfacing costs were based on California data which for certain items have only recently been made the subject of special study. The resurfacing cost item which is most likely to be questioned, especially by economists, is the increased cost resulting from the application of a 2 percent compound interest price-trend factor. Thus, for resurfacing at the end of the 18th year, the 1960 costs were increased 42.8 percent; at the end of the 26th year, the increase was 67.3 percent; and for resurfacing at the end of the 31st year, the 1960 costs were increased by 84.8 percent. It is evident that the 2 percent price-trend factor will result in a substantial increase in resurfacing costs and that special consideration should be given to the advisability of using such a factor in other studies, and its amount if used. In the following discussion some of the arguments for and against the adoption of a price-trend factor are presented.

In the Federal Interagency report (11) on Proposed Practices for Economic Analysis of River Basin Projects, a committee composed of some of the nation's leading economists recommended that in making benefit-cost analyses for the evaluation of Federal public works projects, "prices should be used which may reasonably be expected to prevail at the time costs are incurred and at the time benefits are realized, in terms of a constant general price level." The Committee also recommended that projected prices should be used for evaluating project benefits as well as costs of maintenance, replacements and deferred construction. However, representatives of several Federal agencies recommended that current prices should be used in estimating all benefits and costs until improved procedures are developed for estimating long-range price projections.

Highway construction costs as indicated by the California Highway Cost Index increased at an average rate of $4\frac{1}{2}$ percent compounded annually for the period from 1940 to 1962. A large part of this increase was brought about as the result of inflation or the depreciation in value of the dollar. During the past 10 years the California Highway Cost Index and the average cost of pavement construction increased at an average rate of 2 percent compounded annually. During this period the general price level was fairly stable and it was partly for this reason that a 2 percent price-trend factor for resurfacing costs was adopted for this study. Another reason for applying a 2 percent price-trend factor was to make allowance for the increased future resurfacing costs which are likely to result from the depletion of the best and most accessible sources of paving materials in California. At the present accelerated rate of highway construction, many of the best sources of paving materials are being exhausted. To develop new sources of paving materials will, in many areas, increase the cost of these materials. The costs of processing the materials to meet specifications and of shipping them over greater distances may also increase their cost.

Estimating future resurfacing costs is complicated by the possibility that technological improvements in plant operations and in the construction of pavements may offset in part the increased cost of future resurfacing referred to above. The authors adopted the 2 percent price-trend factor currently being used by the California Division of Highways, recognizing that it represents a value judgment which is open to question. In a critical evaluation of pavement costs, the adoption of a price-trend factor should be given special consideration for projects where unit costs might rise substantially for such reasons as the decreasing accessibility and availability of suitable paving materials.

The 10 percent charge for preliminary and construction engineering work required in connection with resurfacing and the 6 percent charge for supplemental work represent average or typical charges for this type of work on state highways in California. The preparation of plans and specifications, the letting of contracts, the testing of materials, providing inspection and engineering supervision on the project, are cost items which can be estimated fairly accurately for a given project. The supplemental work which includes traffic handling, placing temporary traffic stripes and traffic signs or signals, replacing permanent traffic stripes, the protection or temporary removal of guardrail and guide posts, and the adjustment or reconstruction of various drainage structures or facilities will vary for each project and instead of using a 6 percent charge, an itemized estimate of the cost of supplemental work should preferably be made for each project.

The traffic delay and accident costs resulting from resurfacing operations adopted for this study were based on California's limited experience in collecting this type of cost data. Traffic delays caused by maintenance and resurfacing operations are now under investigation by the Division of Highways Traffic Department and it is expected that more accurate and reliable data will be available within a year or two. It should be noted in Tables 10 to 14 that the estimated traffic delay and accident costs were assigned the low value of \$20 per mile of rigid pavement for light-duty roads and were increased to \$300 per mile of rigid pavement for heavy-duty roads. Due to the reduction in resurfacing thickness of the asphalt concrete pavements and the reduction in time required for resurfacing these pavements, the traffic delay costs for the flexible pavements were reduced approximately in proportion to the change in the thickness of the resurfacing of the two pavement types. For the same reason, the traffic delay and accident costs for resurfacing shoulders were lower than the same costs for resurfacing the traveled way portion of the roadway.

In comparing the various charges for resurfacing given in Tables 10 to 14, it is evident that the charges for traffic delay and accident costs used in this study are so small that for all practical purposes they could have been omitted. An important consideration, however, in this connection is that in the selection of pavement type for urban freeways with traffic volumes ranging from 50,000 to 200,000 vehicles per day, portland cement concrete has generally been selected as the preferred pavement type in California because the traffic delays and accident hazards created by pavement repairs and resurfacing have been assumed to be much greater on asphalt concrete pavements than on portland cement concrete pavements. This study indicated that the magnitude and importance of the traffic delay and accident costs in the selection of pavement type for urban freeways have been greatly exaggerated. There is evident need for conducting factual studies to determine the true nature of these costs.

As in many other highway cost studies involving traffic accidents, it will be very difficult to establish the traffic accident costs caused by resurfacing. Nevertheless, it is important that studies to determine the accident experience in connection with pavement repairs and resurfacing operations be conducted to ascertain the nature and extent of these accidents. Maintenance departments have in recent years developed traffic control safeguards which are reducing traffic delays and the accident hazards on freeways caused by pavement repairs and resurfacing operations. While the use of extensive specially developed traffic control measures will increase the cost of resurfacing, they should contribute to a reduction in the accident hazards and the accident costs and make it possible to obtain a more accurate estimate of the accident costs to be charged against the resurfacing operations.

Maintenance Costs

The maintenance costs for this study were assumed to cover all routine and periodic maintenance of the traveled way and shoulder portion of the roadway, expressed in terms of the average annual maintenance cost per mile of 2-lane roadway. The maintenance costs for each pavement type are given in Tables 15, 16, 17, and 18. For the portland cement concrete pavements with service lives of 18 and 26 years and an analysis period of 26 years, an average annual maintenance cost of $320 per mile was used. For a 39-yr analysis period, the average annual cost was increased to $370

TABLE 15

ANNUAL COSTS OF A 2-LANE MILE OF PORTLAND CEMENT CONCRETE PAVEMENT AND SHOULDERS FOR NINE TYPICAL DESIGN SECTIONS FOR A 26-YR ANALYSIS PERIOD[a]

Design Section			Contract Price Rating	Annual Costs of Pavement and Shoulders for 26-Yr Analysis Period				
No.	R-Value of Soil	Traffic Index		Initial Construction Costs ($)		Maintenance Costs ($)	Total Annual Costs per Mile ($)	
				3%	6%		3%	6%
1	R 5	8.5	Low	3,380	4,650	320	3,700	4,970
			High	5,720	7,870	320	6,040	8,190
			Avg.	4,320	5,940	320	4,640	6,260
2		10.0	Low	4,040	5,550	320	4,360	5,870
			High	6,840	9,420	320	7,160	9,740
			Avg.	5,190	7,130	320	5,510	7,450
3		11.5	Low	4,110	5,660	320	4,430	5,980
			High	7,140	9,830	320	7,460	10,150
			Avg.	5,330	7,340	320	5,650	7,660
7	R 35	8.5	Low	3,300	4,540	320	3,620	4,860
			High	5,420	7,460	320	5,740	7,780
			Avg.	4,170	5,730	320	4,490	6,050
8		10.0	Low	3,890	5,350	320	4,210	5,670
			High	6,250	8,590	320	6,570	8,910
			Avg.	4,890	6,720	320	5,210	7,040
9		11.5	Low	3,970	5,460	320	4,290	5,780
			High	6,550	9,010	320	6,870	9,330
			Avg.	5,030	6,930	320	5,350	7,250
13	R 65	8.5	Low	3,080	4,230	320	3,400	4,550
			High	4,520	6,220	320	4,840	6,540
			Avg.	3,720	5,110	320	4,040	5,430
14		10.0	Low	3,670	5,040	320	3,990	5,360
			High	5,350	7,360	320	5,670	7,680
			Avg.	4,440	6,110	320	4,760	6,430
15		11.5	Low	3,670	5,040	320	3,990	5,360
			High	5,350	7,360	320	5,670	7,680
			Avg.	4,440	6,110	320	4,760	6,430

[a]Interest at 3 and 6%; service life of portland cement concrete pavement = 26 yr.

REFERENCES

1. Informational Guide on Project Procedures. AASHO, Nov. 1960.
2. Planning Manual of Instructions, Part 7—Design. California Div. of Highways, May 1963.
3. Agg, T. R. Report of Committee on Highway Transportation Costs. HRB Proc., Vol. 9, pp. 360-368, 1929.
4. Baldock, R. H. The Annual Cost of Highways. Highway Research Record No. 12, pp. 91-111, 1963.
5. Breed, C. B. Road Costs as Affected by Reconstruction on State Highway Route No. 12, Worcester County, Massachusetts. HRB Proc., Vol. 14, Pt. 1, pp. 60-69, 1934.
6. Economics of Asphalt and Concrete for Highway Construction. Stanford Res. Inst., 1961.
7. Economic Comparison of Pavement Types. California Div. of Highways, Circ. Letter No. 63-169, June 1963.
8. Hveem, F. N., and Sherman, G. B. Thickness of Flexible Pavements by the California Formula Compared to AASHO Road Test Data. Highway Research Record No. 13, pp. 142-166, 1963.
9. Pavement Cost Study—State of California Highway Projects Contracted in 1960. Asphalt Inst., Pacific Coast Div., Jan. 1961.
10. Contract Item Data Report for 1960. California Div. of Highways, 1960.
11. Proposal Practices for Economic Analysis of River Basin Projects. U. S. Inter-Agency Comm. on Water Resources, Subcomm. on Evaluation Stan., 1958.
12. Maintenance Manual of Instructions. 5th Ed. California Div. of Highways, 1958.
13. Engineering Analysis of the Stanford Research Institute—American Petroleum Institute Study. Portland Cement Assoc., April 1962.
14. Gronberg, G. D., and Blosser, N. B. Lives of Highway Surfaces—Half-Century Trends. Public Roads, June 1956.

6. In view of the wide range in the unit prices for paving projects in all parts of California, this investigation clearly demonstrates that it is most important to make pavement cost comparisons on a project-by-project basis using the structural design, traffic and cost data which apply to the particular area and project under consideration instead of using statewide cost data.

7. Estimates for future resurfacing costs should be made with due consideration for all resurfacing cost factors recommended by the California Division of Highways in their 1963 instructions for making pavement cost comparisons. Items to be evaluated are a price-trend factor, preliminary and construction engineering costs, and traffic delay and accident costs resulting from resurfacing operations. The use of a price-trend factor to compute future resurfacing costs is not recommended if the factor represents an increase in future costs resulting from inflation.

8. This study indicated that the importance of traffic delay and accident costs during maintenance and resurfacing operations as a major factor in the selection of the pavement type for urban freeways appears to have been grossly exaggerated. Factual studies are needed to determine the true nature and importance of these costs.

9. Changing the interest rate from 3 to 6 percent had no significant effect in a comparison of annual costs for heavy-duty pavements where the initial construction costs for both pavement types were within the same price range. The greatest effect resulting from a change in the interest rate was obtained for pavement sections where the construction costs of the portland cement concrete pavements were 50 percent or more higher than the construction costs for asphalt concrete pavements. However, under these conditions, it was the high initial construction cost and not the high interest charges which was the controlling factor in the selection of pavement type on a cost comparison basis.

10. With annual maintenance costs ranging from $320 to $520 per mile as compared to total annual costs which generally ranged from $4,000 to $8,000 per mile, it is evident that maintenance costs will generally have no significant influence in the selection of pavement type on a cost comparison basis.

11. Reducing the service life of both pavement types resulted in an increase in the number of resurfacings required and in an increase in resurfacing costs. The effect of these changes was greatest for asphalt concrete pavements with the shortest service lives. For certain pavement sections the additional resurfacing costs increased the annual costs of the asphalt concrete pavements to about the same annual cost level as the annual costs for portland cement concrete pavements.

12. Extending the analysis period from 26 years to 39 years increased the number of resurfacings required for both pavement types and also increased the cost of resurfacings. In view of the difficulties in establishing accurate estimates of the cost of resurfacings for a 26-yr analysis period and the compounding of these difficulties and inaccuracies when the analysis period is extended to 39 years, an analysis period in the range of 20 to 30 years, or not greater than the average service life of portland cement concrete pavements in the area, is recommended for use in making pavement cost comparisons on a project-by-project basis.

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lishing accurate estimates of resurfacing costs. The above analysis also gives added support to the method adopted by the California Division of Highways in 1963 for selecting the analysis period. For making pavement cost comparisons their instructions state that an economic analysis period shall be chosen for each project based on the average service life of concrete pavements in the area that have served under comparable conditions. According to these instructions no resurfacing costs would have to be computed for the portland cement concrete pavements and generally only the cost for one resurfacing would be required for asphalt concrete pavements.

In the foregoing analysis of the effects and significance of the various pavement cost items in relation to the annual costs of pavements, it is evident that the two major items are the initial construction costs and the resurfacing costs. By reducing the analysis period to 26 years or to the average service life of portland cement concrete pavements in the area where the pavement cost comparisions are being made, the variable percentages or estimates for the resurfacing costs can be minimized and the accuracy and reliability of the pavement cost comparisons can be greatly improved. While the above analysis indicates that the average maintenance costs for asphalt concrete pavements will account for 6 to 16 percent of the total annual costs and for portland cement concrete pavements the corresponding costs will amount to only 4 to 8 percent of the total annual costs, these values are so small when compared to the 70 to 95 percentage values for the initial construction costs, that only in rare cases will the maintenance costs have a significant influence in the selection of pavement types on a cost comparison basis.

SUMMARY AND CONCLUSIONS

A basic requirement for the economic design and construction of high-type pavements for our nation's interstate and state highways costing many billions of dollars each year is the selection of pavement type, rigid or flexible, based upon a well-documented economic analysis and design procedure. It is the contention of the authors that the principal factors governing the selection of pavement type can be evaluated on a reasonably sound, rational, and factual basis, using approved formulas for the structural design of both rigid and flexible pavements and a basic formula for making pavement cost comparisons.

A major objective of this study was to establish the effect and significance of each of six variables in the basic formula for making pavement cost comparisons. The most significant results and conclusions reached as the result of this investigation are the following:

1. The initial construction cost was found to be the most decisive factor in a comparison of the annual costs of pavements. It overshadowed the variable effects of such factors as maintenance and resurfacing costs, rate of interest, pavement service life and the analysis period.
2. For the majority of pavement sections covered by this study, the initial construction costs constituted 85 to 95 percent of the total annual costs while the maintenance costs amounted to less than 10 percent of the total annual costs.
3. In general, the annual costs of rigid and flexible pavements designed for poor soil conditions were mostly within the same price bracket, but the costs of the rigid pavements designed for excellent soil conditions were 25 to 40 percent higher than those of flexible pavements designed for these same conditions.
4. An analysis of the costs of flexible pavements with three different types of base construction indicated that under certain specific traffic and soil conditions each type of base provided a definite cost advantage which could and should be evaluated.
5. In the construction cost analysis, the contract prices for each cost item for 155 paving projects for which contracts were awarded in California in 1960 were rated in terms of high, low and average bid prices. For the same heavy-duty pavement design section, the construction costs for asphalt concrete pavements ranged from \$65,000 to \$130,000 as compared with \$74,000 to \$128,000 per two-lane mile for portland cement concrete pavements. For the same light-duty pavement design sections, the construction costs for asphalt concrete pavements ranged from \$28,000 to \$50,000 as compared with \$55,000 to \$89,000 per two-lane mile for portland cement concrete pavements.

in Figures 9 and 10 except that the analysis period was increased from 26 years to 39 years. The most important new feature in the cost comparisons for the 39-yr analysis period was the need for two resurfacings for the asphalt concrete pavements and of one resurfacing for portland cement concrete pavements where for the 26-yr analysis period only one resurfacing was required for the asphalt concrete pavement and no resurfacing was required for the portland cement concrete pavements.

As a result of the additional resurfacing costs, the distribution of annual costs on a percentage basis was altered considerably, especially for the asphalt concrete pavements where two resurfacings were required. Thus, the data in Figure 11 show that the greatest change was the reduction in the percentage for the initial construction costs of the asphalt concrete for which the percentages of total annual costs were as low as 50 to 60 percent. Under these same conditions, there was a corresponding increase in the combined percentages for resurfacing and maintenance costs and in the salvage value. The percentages for resurfacing costs were increased to 20 and 25 percent, for maintenance costs to 10 and 15 percent and the salvage value to 4 and 5 percent (negative).

For the 39-yr analysis period the lowest resurfacing costs on a percentage basis are shown in Figure 12 for portland cement concrete pavements with average values of 8 to 11 percent. For the same conditions the percentages for maintenance costs ranged from 4 to 6 percent. The resurfacing costs for the portland cement concrete pavements are lower than for the asphalt concrete pavements because only one resurfacing was required for the portland cement concrete pavements and two resurfacings were required for the asphalt concrete pavements.

In Tables 21 to 24, numerical values are given for the itemized annual costs on a percentage basis for the same pavement sections for which the itemized costs are given in Figures 9 to 12 except that for the annual costs in Tables 21 to 24 the service life of the asphalt concrete pavements was reduced to 13 years and for the portland cement concrete to 18 years instead of 18-yr and 26-yr service lives used to compute the annual costs in Figures 9 to 12. A significant feature of the data in Table 23 was brought about by the 18-yr service life of the portland cement concrete pavements which required two resurfacings for the portland cement concrete or the same number as for the asphalt concrete pavements for which the corresponding annual cost data are given in Table 24. The average resurfacing costs for the portland cement concrete pavements under these conditions ranged from 23 to 29 percent of the total annual costs with interest at 3 percent as compared with 19 to 28 percent for the asphalt concrete pavements. With interest at 6 percent the resurfacing costs for portland cement concrete were reduced to values of from 14 to 17 percent and for asphalt concrete to values ranging from 12 to 23 percent. The percentage values for the average costs in Tables 23 and 24 ranged from 5 to 6 percent of the total annual cost for portland cement concrete pavements and from 7 to 11 percent for the asphalt concrete pavements.

The analysis of annual pavement costs on a percentage basis clearly shows the importance of the initial construction costs as the dominant factor in a comparison of annual costs of pavements where no resurfacing or where only one resurfacing is required. In a cost analysis where two resurfacings are required, the annual costs for resurfacing may reach percentage values as high as 32 percent of the total annual cost and the initial construction costs may be as low as 52 percent of the total annual cost.

In the discussion of the methods used to establish the resurfacing costs for both pavement types in this study, the authors indicated the difficulties encountered in establishing accurate estimates for the costs of certain items and the questionable use of a price-trend factor in establishing the cost of future resurfacings. It is obvious that if it is difficult to establish an accurate estimate for the annual cost of one resurfacing for an analysis period of 26 years, these difficulties will be compounded when an attempt is made to estimate the annual cost of two resurfacings.

On the basis of the above analysis of resurfacing costs for a 26-yr analysis period and a 39-yr analysis period, the evidence presented clearly supports the recommendation that a 26-yr period of analysis should be used in preference to a 39-yr period of analysis. The adoption of a 26-yr analysis period should greatly reduce the difficulties in estaband of 4 to 6 percent for asphalt concrete pavements. Thus, expressing the annual costs on a percentage basis does not disclose the wide spread in the contract prices for the initial construction costs from high to low shown in Figures 3 to 8.

The use of the terms high and low for the annual maintenance costs in Figures 9 and 11 requires a special explanation. Actually, for the conditions in each chart, a constant maintenance cost was used and the maintenance costs on a percentage basis shown in these charts were computed in terms of the corresponding high and low initial construction costs. Thus, for portland cement concrete pavements with a service life of 26 years and a TI of 8. 5, for a high initial construction annual cost amounting to 95 percent of the total annual cost, the corresponding maintenance cost on the chart shown as "high" is 5 percent; for a low initial construction annual cost of 92 percent, the corresponding maintenance cost on the chart shown as "low" is 8 percent.

When resurfacing costs and salvage value are included in the annual cost computations on a percentage basis, as was necessary in computing the annual costs for the asphalt concrete pavements shown in Figures 9 and 10, the percentages for initial construction annual costs are 10 to 20 percent lower for the asphalt concrete pavements than for the corresponding values for the portland cement concrete pavements. Thus, the combined effect of maintenance and resurfacing costs and of salvage value constitute a significant part of the total annual cost of asphalt concrete pavements which should be taken into account when making cost comparisons in the selection of pavement types.

Another factor which contributed to the marked change in the percentage values for the itemized annual costs of asphalt concrete pavements versus the values for portland cement concrete pavements was the large reduction in the initial construction costs for a majority of the asphalt concrete pavement sections when compared with the corresponding costs for the portland cement concrete pavement sections. For the asphalt concrete pavement sections with low initial construction costs and with relatively high maintenance and resurfacing costs, the percentages for the average initial construction costs ranged from 70 to 90 percent of the total annual costs as compared with 92 to 95 percent for portland cement concrete pavements. The percentages for maintenance costs were 4 to 5 percent higher for asphalt concrete pavements than for portland cement concrete pavements. In addition, the resurfacing costs and salvage value for asphalt concrete pavements introduced an additional 5 to 10 percent differential in annual costs for asphalt concrete versus portland cement concrete pavements.

In Figures 9 and 10 the salvage values are referred to as negative annual cost values. In the annual cost formula recommended by Baldock and adopted for use in this study, the salvage value represents a residual value in the final resurfacing of a pavement where the estimated life of the resurfacing extends beyond the analysis period. Therefore, to obtain what might be considered as the net annual cost of resurfacing, the salvage values should be subtracted from the resurfacing costs. It is interesting to note that for the data shown in Figures 9 and 10, if the correction for salvage value on annual costs had been made as indicated above, the net annual cost of resurfacing would then have been approximately the same as the annual maintenance cost on a percentage basis. While there is some similarity in pavement maintenance and resurfacing operations, the annual costs for these operations are established on an entirely different basis. Thus, while these costs were the same for the conditions for which the annual costs were computed for the pavement sections in Figures 9 and 10, it will be shown later that they are not the same for the conditions for which annual costs are given in Figures 11 and 12.

The relative effect of using a 6 percent interest rate versus a 3 percent rate is also shown in Figures 9 and 10. The most significant effect of a change in interest rates was the 2 to 5 percent increase of the annual cost percentages for the initial construction costs when a 6 percent rate was used instead of a 3 percent rate. Of course, for these same conditions there was a corresponding reduction in the combined percentages for the resurfacing and maintenance costs. The percentage change due to a change in interest rate was greater for flexible pavements than for rigid pavements.

In Figures 11 and 12 the itemized costs on a percentage basis are shown for the same pavement sections and cost data as were used for developing the values shown

TABLE 23

ANNUAL COSTS ON A PERCENTAGE BASIS OF A 2-LANE MILE OF PORTLAND CEMENT CONCRETE PAVEMENT AND SHOULDERS FOR NINE TYPICAL DESIGN SECTIONS FOR 39-YR ANALYSIS PERIOD[a]

Design Section			Contract Price Rating	Annual Costs in Percent of Total Annual Costs for Pavement and Shoulders								
No.	R-Value of Soil	Traffic Index		Initial Construction Costs		Resurfacing Costs		Salvage Value (-)		Maintenance Costs		Total Annual Cost
				3%	6%	3%	6%	3%	6%	3%	6%	3% and 6%
1	R 5	8.5	Low	67.2	77.3	26.5	16.7	-3.1	-1.1	9.4	7.1	100.0
			High	71.5	81.4	25.3	15.3	-2.7	-1.1	5.9	4.4	100.0
			Avg.	68.4	78.9	26.9	16.5	-2.8	-1.1	7.5	5.7	100.0
2		10.0	Low	70.7	80.3	23.7	14.5	-2.7	-1.0	8.3	6.2	100.0
			High	75.0	83.6	22.2	13.5	-2.4	-0.9	5.2	3.8	100.0
			Avg.	72.3	81.7	23.6	14.3	-2.5	-0.9	6.6	4.9	100.0
3		11.5	Low	70.8	80.6	23.7	14.3	-2.6	-1.0	8.1	6.1	100.0
			High	75.5	84.2	21.8	13.0	-2.3	-0.9	5.0	3.7	100.0
			Avg.	72.6	82.0	23.4	14.1	-2.4	-0.9	6.4	4.8	100.0
7	R 35	8.5	Low	66.8	77.0	26.8	17.0	-3.1	-1.2	9.5	7.2	100.0
			High	70.3	80.5	26.4	16.0	-2.8	-1.1	6.1	4.6	100.0
			Avg.	67.7	78.3	27.5	17.0	-2.9	-1.1	7.7	5.8	100.0
8		10.0	Low	70.0	79.8	24.3	14.9	-2.8	-1.0	8.5	6.3	100.0
			High	73.2	82.3	23.8	14.6	-2.5	-1.0	5.5	4.1	100.0
			Avg.	71.0	80.8	24.7	15.1	-2.6	-1.0	6.9	5.1	100.0
9		11.5	Low	70.1	80.1	24.3	14.7	-2.7	-1.0	8.3	6.2	100.0
			High	73.8	83.1	23.3	14.0	-2.4	-1.0	5.3	3.9	100.0
			Avg.	71.4	81.1	24.4	14.8	-2.5	-0.9	6.7	5.0	100.0
13	R 65	8.5	Low	65.2	75.7	28.0	17.9	-3.2	-1.2	10.0	7.6	100.0
			High	66.5	77.5	29.8	18.5	-3.2	-1.3	6.9	5.3	100.0
			Avg.	65.1	76.3	29.7	18.5	-3.1	-1.2	8.3	6.4	100.0
14		10.0	Low	68.8	78.8	25.3	15.6	-2.9	-1.1	8.8	6.7	100.0
			High	70.0	80.0	26.6	16.5	-2.8	-1.1	6.2	4.6	100.0
			Avg.	69.1	79.2	26.4	16.3	-2.8	-1.0	7.3	5.5	100.0
15		11.5	Low	68.4	78.8	25.6	15.6	-2.8	-1.1	8.8	6.7	100.0
			High	69.6	80.0	27.0	16.5	-2.8	-1.1	6.2	4.6	100.0
			Avg.	68.8	79.1	26.7	16.4	-2.8	-1.0	7.3	5.5	100.0

[a]Service life of portland cement concrete pavement = 18 yr; service life of resurfacing = 13 yr; interest at 3 and 6%.

TABLE 24

ANNUAL COSTS ON A PERCENTAGE BASIS OF A 2-LANE MILE OF ASPHALT CONCRETE PAVEMENT AND SHOULDERS FOR NINE TYPICAL DESIGN SECTIONS FOR 39-YR ANALYSIS PERIOD[a]

Design Section			Contract Price Rating	Annual Costs in Percent of Total Annual Costs for Pavement and Shoulders						
No.	R-Value of Soil	Traffic Index		Initial Construction Costs		Resurfacing Costs		Maintenance Costs		Total Annual Costs
				3%	6%	3%	6%	3%	6%	3% and 6%
1	R 5	8.5	Low	59.4	70.5	24.8	17.2	15.8	12.3	100.0
			High	68.7	78.3	22.0	14.8	9.3	6.9	100.0
			Avg.	63.9	74.4	23.9	16.3	12.2	9.3	100.0
2		10.0	Low	64.8	75.0	21.5	14.6	13.7	10.4	100.0
			High	73.0	81.7	19.0	12.5	8.0	5.8	100.0
			Avg.	67.9	78.0	21.1	14.0	11.0	8.0	100.0
3		11.5	Low	68.1	77.7	19.6	13.2	12.3	9.1	100.0
			High	75.9	83.8	17.0	11.0	7.1	5.2	100.0
			Avg.	71.4	80.4	19.0	12.5	9.6	7.1	100.0
7	R 35	8.5	Low	55.5	67.0	27.2	19.3	17.3	13.7	100.0
			High	60.7	71.7	27.6	19.3	11.7	9.0	100.0
			Avg.	58.2	69.5	27.7	19.4	14.1	11.1	100.0
8		10.0	Low	61.6	72.3	23.5	16.2	14.9	11.5	100.0
			High	66.1	76.2	23.9	16.2	10.0	7.6	100.0
			Avg.	63.2	73.9	24.4	16.6	12.4	9.5	100.0
9		11.5	Low	65.0	75.1	21.5	14.7	13.5	10.2	100.0
			High	69.5	79.0	21.5	14.3	9.0	6.7	100.0
			Avg.	66.6	76.7	22.2	14.8	11.2	8.5	100.0
13	R 65	8.5	Low	47.9	59.8	31.9	23.5	20.2	16.7	100.0
			High	55.8	67.4	31.1	22.2	13.1	10.4	100.0
			Avg.	52.3	64.3	31.6	22.7	16.1	13.0	100.0
14		10.0	Low	54.2	65.9	28.0	19.9	17.8	14.2	100.0
			High	61.5	72.4	27.1	18.8	11.4	8.8	100.0
			Avg.	57.6	69.0	28.1	19.7	14.3	11.3	100.0
15		11.5	Low	59.2	70.1	25.1	17.7	15.7	12.2	100.0
			High	65.8	76.1	24.1	16.3	10.1	7.6	100.0
			Avg.	62.1	73.0	25.2	17.2	12.7	9.8	100.0

[a]Service life of asphalt concrete pavement = 13 yr; service life of resurfacing = 13 yr; interest at 3 and 6%.

TABLE 21

ANNUAL COSTS ON A PERCENTAGE BASIS OF A 2-LANE MILE OF PORTLAND CEMENT CONCRETE PAVEMENT AND SHOULDERS FOR NINE TYPICAL DESIGN SECTIONS FOR 26-YR ANALYSIS PERIOD[a]

Design Section			Contract Price Rating	Annual Costs in Percent of Total Annual Cost for Pavement and Shoulders								
No.	R-Value of Soil	Traffic Index		Initial Construction Costs		Resurfacing Costs		Salvage Value (-)		Maintenance Costs		Total Annual Cost
				3%	6%	3%	6%	3%	6%	3%	6%	3% and 6%
1	R 5	8.5	Low	78.4	84.4	20.2	12.9	-6.0	-3.1	7.4	5.8	100.0
			High	82.1	87.3	19.2	12.2	-5.9	-3.0	4.6	3.5	100.0
			Avg.	79.4	85.3	20.8	13.3	-6.1	-3.2	5.9	4.6	100.0
2		10.0	Low	81.1	86.4	17.7	11.2	-5.2	-2.6	6.4	5.0	100.0
			High	84.5	89.1	16.7	10.5	-5.1	-2.6	3.9	3.0	100.0
			Avg.	82.4	87.5	18.1	11.4	-5.6	-2.8	5.1	3.9	100.0
3		11.5	Low	81.2	86.7	17.6	11.2	-5.1	-2.8	6.3	4.9	100.0
			High	84.9	89.5	16.2	10.1	-4.9	-2.5	3.8	2.9	100.0
			Avg.	82.6	87.7	17.8	11.2	-5.4	-2.7	5.0	3.8	100.0
7	R 35	8.5	Low	77.9	84.1	20.6	13.2	-6.1	-3.2	7.6	5.9	100.0
			High	81.2	86.6	20.1	12.8	-6.1	-3.1	4.8	3.7	100.0
			Avg.	78.8	84.8	21.4	13.8	-6.2	-3.3	6.0	4.7	100.0
8		10.0	Low	80.6	86.0	18.2	11.6	-5.4	-2.7	6.6	5.1	100.0
			High	83.2	88.1	18.0	11.4	-5.5	-2.8	4.3	3.3	100.0
			Avg.	81.5	86.9	19.0	12.0	-5.8	-3.0	5.3	4.1	100.0
9		11.5	Low	80.7	86.2	18.1	11.5	-5.3	-2.8	6.5	5.1	100.0
			High	83.7	88.6	17.4	10.9	-5.2	-2.7	4.1	3.2	100.0
			Avg.	81.8	87.1	18.7	11.8	-5.7	-2.9	5.2	4.0	100.0
13	R 65	8.5	Low	76.8	83.1	21.7	13.9	-6.5	-3.3	8.0	6.3	100.0
			High	78.4	84.5	23.2	14.9	-7.1	-3.7	5.5	4.3	100.0
			Avg.	76.8	83.2	23.4	15.2	-6.8	-3.6	6.6	5.2	100.0
14		10.0	Low	79.6	85.3	19.1	12.2	-5.6	-2.9	6.9	5.4	100.0
			High	81.0	86.4	20.4	13.0	-6.2	-3.2	4.8	3.8	100.0
			Avg.	80.0	85.7	20.5	13.0	-6.3	-3.2	5.8	4.5	100.0
15		11.5	Low	79.4	85.2	19.3	12.4	-5.6	-3.0	6.9	5.4	100.0
			High	80.9	86.4	20.5	13.0	-6.2	-3.2	4.8	3.8	100.0
			Avg.	79.8	85.5	20.7	13.2	-6.3	-3.2	5.8	4.5	100.0

[a]Service life of portland cement concrete pavement = 18 yr; service life of resurfacing = 13 yr; interest at 3 and 6%.

TABLE 22

ANNUAL COSTS ON A PERCENTAGE BASIS OF A 2-LANE MILE OF ASPHALT CONCRETE PAVEMENT AND SHOULDERS FOR NINE TYPICAL DESIGN SECTIONS FOR 26-YR ANALYSIS PERIOD[a]

Design Section			Contract Price Rating	Annual Costs in Percent of Total Annual Costs for Pavement and Shoulders						
No.	R-Value of Soil	Traffic Index		Initial Construction Costs		Resurfacing Costs		Maintenance Costs		Total Annual Cost
				3%	6%	3%	6%	3%	6%	3% and 6%
1	R 5	8.5	Low	70.9	77.5	16.4	12.4	12.7	10.1	100.0
			High	79.1	84.5	13.6	9.9	7.3	5.6	100.0
			Avg.	75.4	81.4	14.9	10.9	9.7	7.7	100.0
2		10.0	Low	75.3	81.3	13.9	10.3	10.8	8.4	100.0
			High	82.5	87.1	11.4	8.2	6.1	4.7	100.0
			Avg.	78.8	84.0	12.8	9.5	8.4	6.5	100.0
3		11.5	Low	78.2	83.5	12.3	9.1	9.5	7.4	100.0
			High	84.5	88.6	10.1	7.3	5.4	4.1	100.0
			Avg.	81.1	85.9	11.5	8.4	7.4	5.7	100.0
7	R 35	8.5	Low	67.3	74.5	18.4	14.0	14.3	11.5	100.0
			High	72.7	79.3	17.8	13.2	9.5	7.5	100.0
			Avg.	70.4	77.4	17.9	13.3	11.7	9.3	100.0
8		10.0	Low	72.6	79.0	15.4	11.5	12.0	9.5	100.0
			High	77.2	82.9	14.8	10.9	8.0	6.2	100.0
			Avg.	74.7	80.7	15.3	11.5	10.0	7.8	100.0
9		11.5	Low	75.6	81.5	13.8	10.2	10.6	8.3	100.0
			High	79.9	84.9	13.1	9.7	7.0	5.4	100.0
			Avg.	77.4	83.0	13.8	10.1	8.8	6.9	100.0
13	R 65	8.5	Low	60.1	68.2	22.5	17.5	17.4	14.3	100.0
			High	68.5	75.7	20.5	15.5	11.0	8.8	100.0
			Avg.	65.5	73.1	20.9	15.8	13.6	11.1	100.0
14		10.0	Low	66.3	73.5	19.0	14.6	14.7	11.9	100.0
			High	73.5	79.9	17.3	12.8	9.2	7.3	100.0
			Avg.	70.1	76.8	18.1	13.8	11.8	9.4	100.0
15		11.5	Low	70.8	77.4	16.4	12.4	12.8	10.2	100.0
			High	77.0	82.6	15.0	11.1	8.0	6.3	100.0
			Avg.	73.7	80.0	16.0	11.9	10.3	8.1	100.0

[a]Service life of asphalt concrete pavement = 13 yr; service life of resurfacing = 13 yr; interest at 3 and 6%.

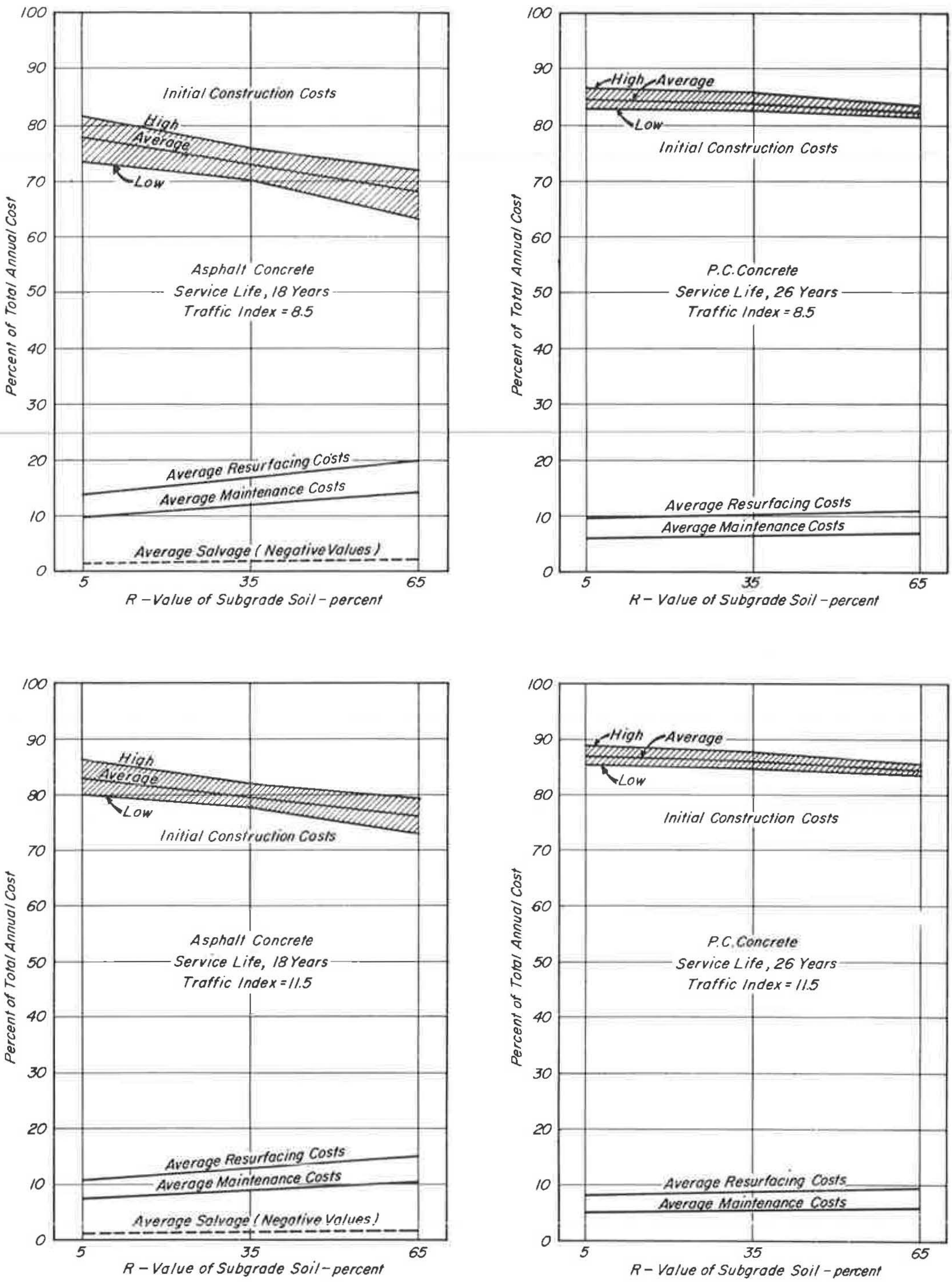

Figure 12. Itemized annual costs in percent of total annual costs for asphalt concrete and portland concrete pavements and shoulders designed for three subgrade soil types, for light-duty traffic (TI = 8.5) and for heavy-duty traffic (TI = 11.5). Service life of the concrete pavements, 26 years, of the asphalt pavements, 18 years, and of the asphalt concrete resurfacing, 13 years; interest, 6%; analysis period, 39 years.

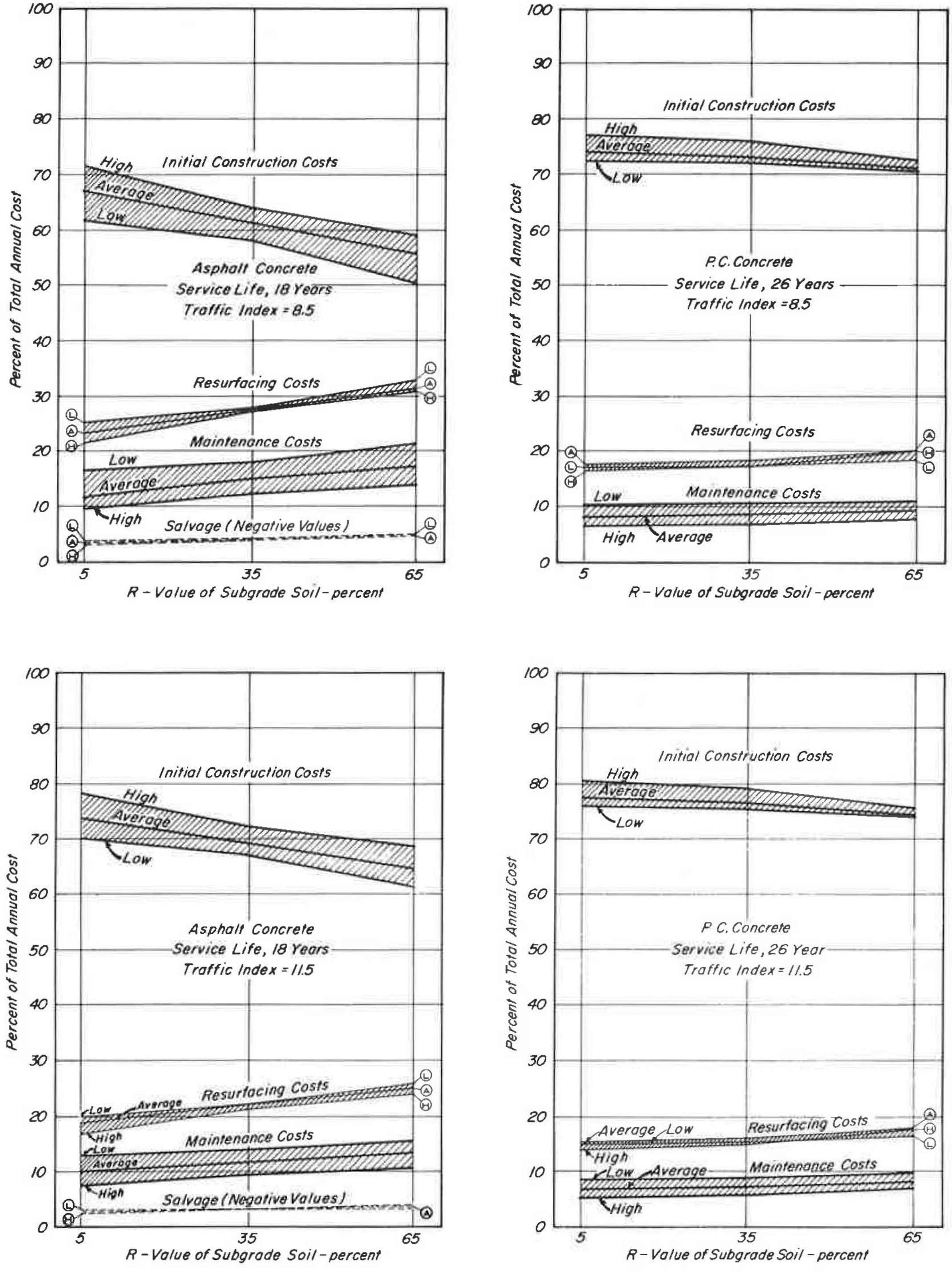

Figure 11. Itemized annual costs in percent of total annual costs for asphalt concrete and portland concrete pavements and shoulders designed for three subgrade soil types, for light-duty traffic (TI = 8.5) and for heavy-duty traffic (TI = 11.5). Service life of the concrete pavements, 26 years, of the asphalt pavements, 18 years, and of the asphalt concrete resurfacing, 13 years; interest, 3%; analysis period, 39 years.

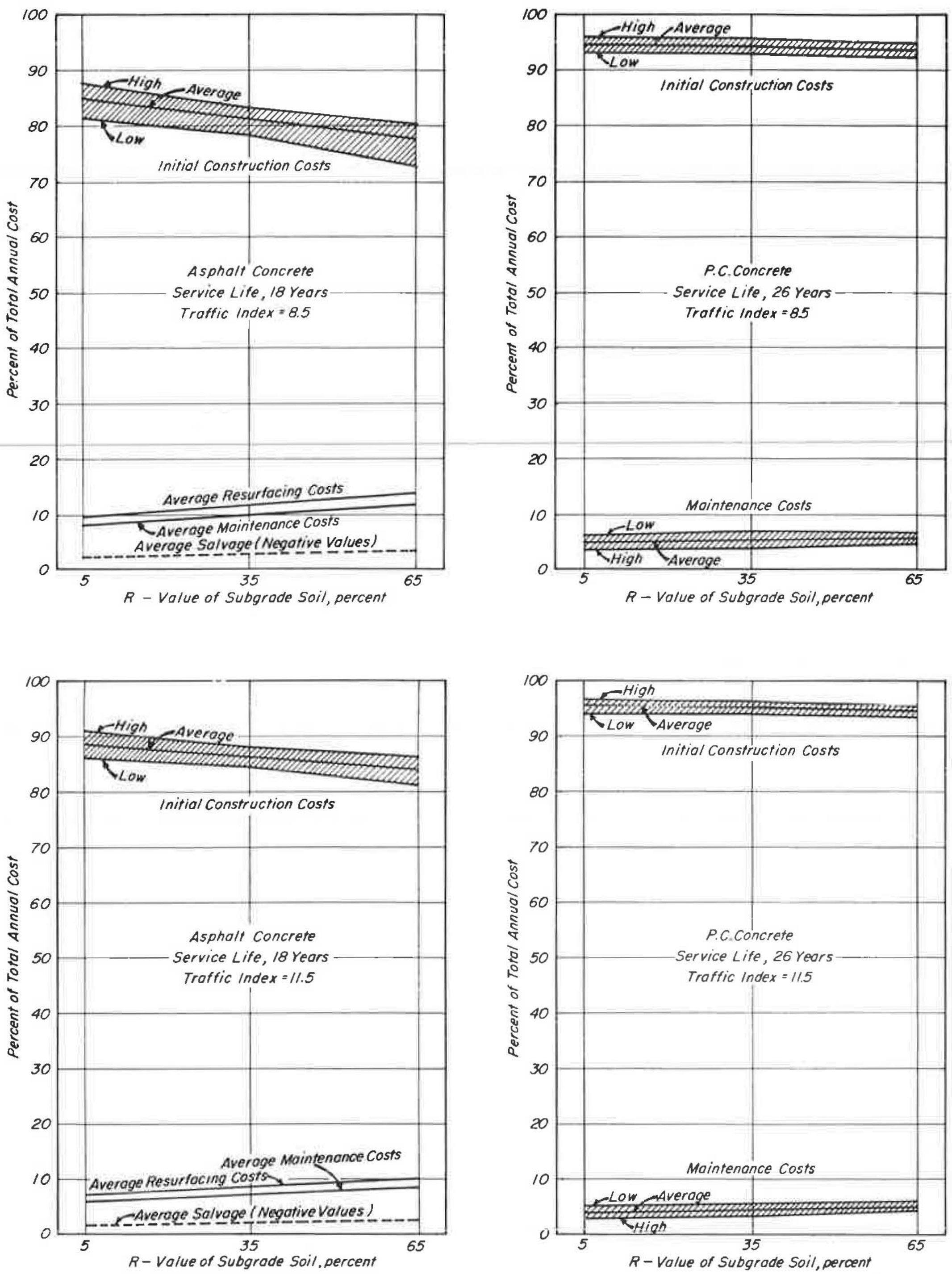

Figure 10. Itemized annual costs in percent of total annual costs for asphalt concrete and portland cement concrete pavements and shoulders designed for three subgrade soil types, for light-duty traffic (TI = 8.5) and for heavy-duty traffic (TI = 11.5). Service life of the concrete pavements, 26 years, and of the asphalt pavements, 18 years; interest rate, 6%; analysis period, 26 years.

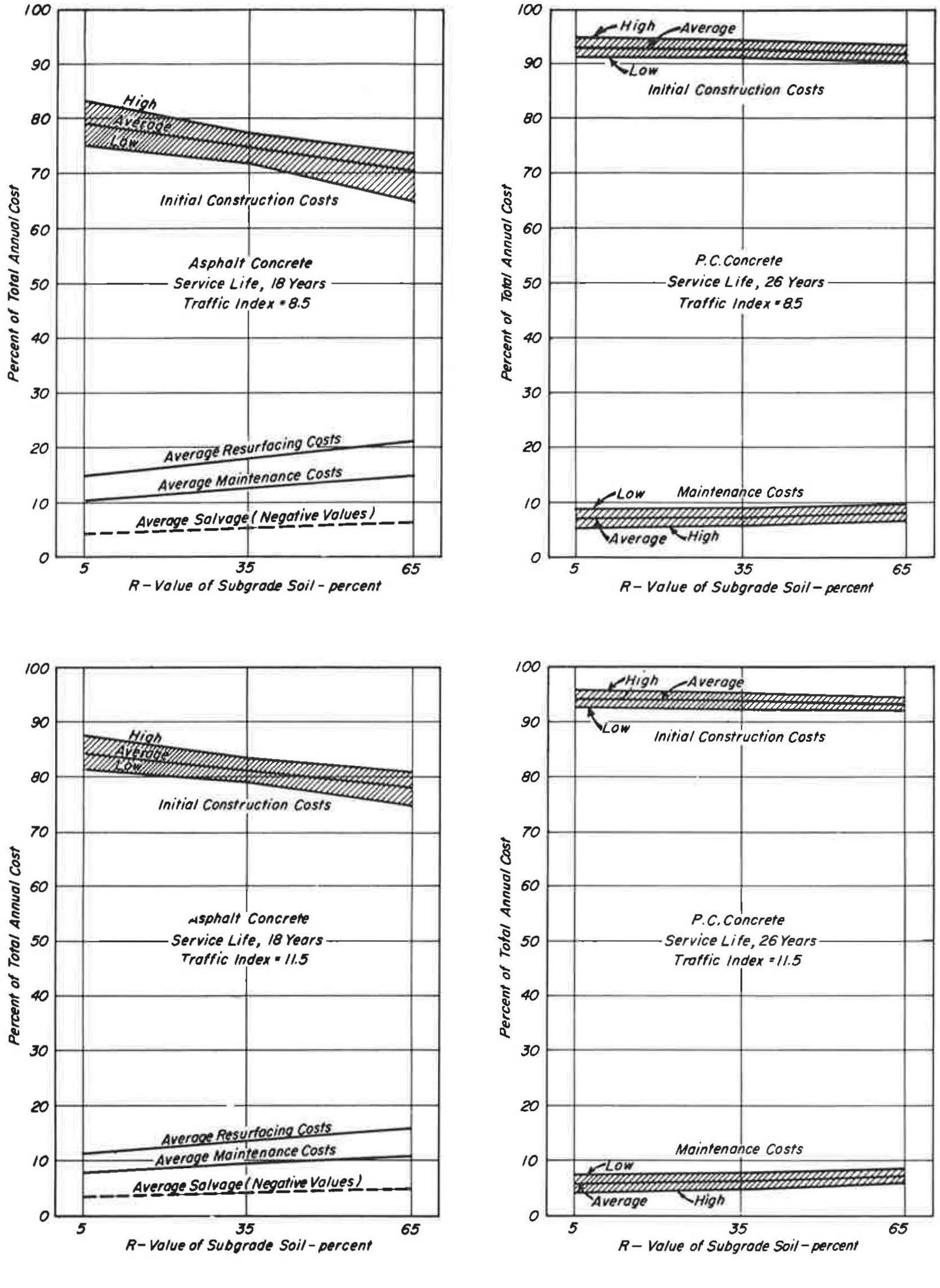

Figure 9. Itemized annual costs in percent of total annual costs for asphalt concrete and portland cement concrete pavements and shoulders designed for three subgrade soil types, for light-duty traffic (TI = 8.5) and for heavy-duty traffic (TI = 11.5). Service life of the concrete pavements, 26 years, and of the asphalt pavements, 18 years; interest rate, 3%; analysis period, 26 years.

ciation Report (13) on pavement economics, extensive maintenance cost data are presented which indicate the variable and unpredictable nature of the maintenance costs for both flexible and rigid pavements. An examination of the maintenance cost data in these reports indicates that only in rare cases will the average annual maintenance cost of either pavement type exceed $1,000 per mile. Where the maintenance costs are exceptionally high, such factors as unusual climatic conditions, soil types, aggregate types, traffic loads, and improper construction are most likely to have contributed to premature pavement failures and to excessive maintenance costs.

For the freeways in the Central Valley area of California, where favorable climatic and soil conditions prevail, our study identified many sections on which the maintenance costs of both rigid and flexible pavements were well below the average values adopted for this study, even though the commercial traffic volume and weights are very high. The average annual maintenance costs adopted for this study were selected to represent statewide average annual maintenance costs. Thus, for pavements in some parts of California, the maintenance costs will be lower than the values used in this study, while in other parts of the state they will be higher. For these reasons, it is important to make pavement cost comparisons on a project-by-project basis instead of making comparisons using statewide average costs.

Maintenance costs can be seen in relation to other costs in Tables 15 through 18. All in all they account for only $320 to $520 of annual costs ranging from $4,000 to $8,000 per mile. Furthermore, the differences in the maintenance costs of the two pavement types are so small that they are not likely to have a significant influence in the selection of pavement type in any case.

RELATIVE EFFECTS OF INITIAL COSTS, RESURFACING COSTS, SALVAGE VALUE AND MAINTENANCE COSTS ON TOTAL ANNUAL COSTS

As a further aid in providing a more complete analysis and evaluation of the relative effects of the itemized annual costs on the total annual costs, all of the itemized annual costs developed in this study have been converted to annual costs on a percentage basis and are shown graphically in Figures 9 to 12 and numerically in Tables 21 to 24.

The charts in Figures 9 and 10 illustrate very effectively all of the important relationships on a percentage basis in a comparison of the itemized annual costs and the total annual costs for both pavement types. The cost data used in these figures represent, in the opinion of the authors, the preferred values for the variables used in this study. Thus, they include percentage values for the itemized annual pavement costs for 3 subgrade soil types, for light- and heavy-duty traffic, for portland cement concrete pavements with a service life of 26 years, for asphalt concrete pavements with a service life of 18 years, for interest rates of 3 and 6 percent and for an analysis period of 26 years.

It should be noted in these charts that with the same analysis period and a service life of 26 years for the portland cement concrete pavements, the percentages of the total annual cost are computed for only two items, the initial construction costs and the maintenance costs. Under these conditions resurfacing of the portland cement concrete pavements is not required and therefore the annual costs for resurfacing and for salvage value are omitted.

The importance of the initial construction costs in pavement cost comparisons is clearly shown in all four charts in Figures 9 and 10, which indicate that in all cases the initial construction costs of portland cement concrete pavements comprise 90 to 95 percent of the total annual costs and that the maintenance costs account for only 5 to 10 percent of the annual costs. The highest percentage values for the initial construction costs were obtained for pavements designed for R 5 soils for either light- or heavy-duty traffic with interest at 6 percent. As the quality of the subgrade soils improved from poor to excellent, the initial construction costs decreased and the annual cost percentages decreased by about 2 percent from 95 percent to 93 percent of the total annual costs.

It is interesting to note in Figures 9 and 10 that the range in initial construction costs in terms of the contract price ratings from high to low, when expressed on a percentage basis, is limited to a narrow band of 2 to 3 percent for the portland cement pavements designed with the same total depth as the traveled way or pavement portion of the roadway. In general, this resulted in lower shoulder depths and costs for the rigid pavements than for the corresponding flexible pavement shoulder sections. Thus, it will be noted in Figures 3 to 6 that while the annual costs of the flexible pavement sections were lower under all conditions than the costs for the corresponding rigid pavement sections, this advantage in lower annual costs for flexible pavements was reduced substantially when the annual costs for the shoulders were combined with the pavement section costs.

It is evident in examining the data shown in Figures 3 to 8 that the trends in annual costs for the pavement sections and for the combined pavement and shoulder sections for the six different soil types and for two different traffic conditions are consistent and that a definite pattern of annual costs is clearly indicated in these charts. To reduce duplications and the complexity of presenting all of the annual cost data for the 144 pavement sections covered by this study in both chart and table form, the charts showing the annual costs for medium-duty traffic (TI = 10.0) were omitted but the annual costs for these pavement sections are shown in table form. Also, the annual costs for pavement sections designed for R 20 and R 80 soils which are shown in Figures 3 to 8 are not listed in Tables 15 to 20. However, in Tables 19 and 20, the annual costs are summarized for a total of 576 pavement cost comparisons representing all combinations of variables of soil types, traffic, interest rates, service lives, analysis periods and contract price ratings for both pavement types.

Effect of a Change in the Interest Rate on the Annual Costs. —The effect on the annual costs of the two pavement types resulting from changing the interest rate from a risk-free rate of three percent to a higher rate of six percent frequently used in engineering economy studies is shown graphically in Figures 3 to 6 and numerically in Tables 19 and 20. The interest charges in this study were influenced by two major factors: (a) the lengths of time chosen for the analysis period and the service lives of the pavements, and (b) the initial construction and future resurfacing costs.

Tables 19 and 20 show how annual costs increase with increased interest rate. When, however, comparison is made between the annual costs of the two pavement types for any given set of conditions, the effect of a higher interest rate is not as great as might be expected. The main reason, as may be noted in Tables 6 to 9, is that while the initial construction costs of the rigid pavements were in practically all cases higher than for flexible pavements, the service lives of the rigid pavements were assumed for this study to be about 50 percent greater than for the flexible pavements. Thus, the higher interest charge attributable to the initial pavement cost is partly offset by the lower annual charge resulting from the longer service life.

Regardless of pavement type, expenses incurred in the latter half of an analysis period yield annual costs which are lower when the interest rate is higher. This is the case with resurfacing costs, as can be seen in Tables 10 to 14 and 16 to 18. These annual costs are sensitive to the analysis period chosen, as can be seen by comparing Tables 16 and 18, both of which are for asphalt concrete pavement and differ only as to analysis period. When comparisons are made for the same analysis period, the effect of interest rate on the difference between annual resurfacing costs for the two pavement types is almost insignificent. This can be seen in Tables 17 and 18, which give costs for the two pavement types for a 39-yr analysis period.

Detailed resurfacing cost data are given in Tables 10 to 14.

In general, the effect of interest rate on total annual costs is governed mainly by initial cost. But it should also be noted that even though changing interest rates from 3 percent to 6 percent had a significant effect on the total annual costs for each pavement type, the difference in the annual costs of the two pavement types obtained for each interest rate was small. Therefore, the decision in the selection of pavement type on a cost comparison basis in this study was not influenced significantly by the interest rates adopted.

Effect of Maintenance Costs on Annual Costs. —One of the significant findings revealed in the annual cost comparisons of flexible and rigid pavements in this study was the relatively minor influence on annual costs which could be attributed to the maintenance cost. In the Stanford Research Institute Report (6) and in the Portland Cement Asso-

TABLE 19

ANNUAL COSTS OF A 2-LANE MILE OF PORTLAND CEMENT CONCRETE PAVEMENT AND SHOULDERS DESIGNED FOR FOUR SUBGRADE SOIL TYPES AND FOR LIGHT-, MEDIUM- AND HEAVY-DUTY TRAFFIC[a]

Int. Rate	Anal. Per. (yr)	Service Life (yr)	Price Rating	Annual Cost of Portland Cement Concrete Pavement and Shoulders per Mile ($)											
				R 5 Soil—Traffic Index			R 35 Soil—Traffic Index			R 50 Soil—Traffic Index			R 65 Soil—Traffic Index		
				8.5	10.0	11.5	8.5	10.0	11.5	8.5	10.0	11.5	8.5	10.0	11.5
3%	26	18	Low	4,310	4,980	5,060	4,230	4,830	4,920	4,230	4,830	4,840	4,010	4,610	4,620
			High	6,970	8,100	8,410	6,670	7,510	7,820	6,670	7,510	7,520	5,770	6,610	6,620
			Avg.	5,440	6,300	6,450	5,290	6,000	6,150	5,290	6,000	6,010	4,840	5,550	5,560
		26	Low	3,700	4,360	4,430	3,620	4,210	4,290	3,620	4,210	4,210	3,400	3,990	3,990
			High	6,040	7,160	7,460	5,740	6,570	6,870	5,740	6,570	6,570	4,840	5,670	5,670
			Avg.	4,640	5,510	5,650	4,490	5,210	5,350	4,490	5,210	5,210	4,040	4,760	4,760
	39	18	Low	3,930	4,470	4,560	3,880	4,360	4,440	3,880	4,360	4,380	3,710	4,190	4,190
			High	6,280	7,150	7,420	6,040	6,690	6,960	6,040	6,690	6,720	5,340	5,980	6,010
			Avg.	4,950	5,630	5,770	4,830	5,390	5,530	4,830	5,390	5,410	4,470	5,040	5,060
		26	Low	3,630	4,160	4,230	3,580	4,050	4,110	3,580	4,050	4,050	3,410	3,880	3,880
			High	5,820	6,690	6,930	5,580	6,230	6,470	5,580	6,230	6,230	4,880	5,520	5,520
			Avg.	4,560	5,250	5,380	4,450	5,010	5,140	4,450	5,010	5,020	4,100	4,660	4,670
6%	26	18	Low	5,510	6,420	6,530	5,400	6,220	6,330	5,400	6,220	6,220	5,090	5,910	5,910
			High	9,020	10,580	10,990	8,610	9,750	10,170	8,610	9,750	9,750	7,370	8,520	8,520
			Avg.	6,970	8,150	8,370	6,760	7,740	7,960	6,760	7,740	7,740	6,140	7,130	7,140
		26	Low	4,970	5,870	5,980	4,860	5,670	5,780	4,860	5,670	5,670	4,550	5,360	5,360
			High	8,190	9,740	10,150	7,780	8,910	9,330	7,780	8,910	8,910	6,540	7,680	7,680
			Avg.	6,260	7,450	7,660	6,050	7,040	7,250	6,050	7,040	7,040	5,430	6,430	6,430
	39	18	Low	5,220	6,010	6,100	5,130	5,830	5,930	5,130	5,830	5,830	4,860	5,560	5,560
			High	8,420	9,790	10,140	8,060	9,070	9,430	8,060	9,070	9,070	6,980	8,000	8,000
			Avg.	6,550	7,600	7,790	6,370	7,240	7,430	6,370	7,240	7,240	5,830	6,700	6,710
		26	Low	4,860	5,650	5,750	4,770	5,470	5,580	4,770	5,470	5,470	4,500	5,200	5,210
			High	7,910	9,250	9,600	7,550	8,530	8,900	7,550	8,530	8,540	6,470	7,460	7,470
			Avg.	6,120	7,160	7,350	5,940	6,800	6,990	5,940	6,800	6,810	5,400	6,260	6,270

[a]Analysis period 26 and 39 yr; service life of concrete pavement, 18 and 26 yr, and of resurfacing, 13 yr; interest at 3 and 6%.

TABLE 20

ANNUAL COSTS OF A 2-LANE MILE OF ASPHALT CONCRETE PAVEMENT AND SHOULDERS DESIGNED FOR FOUR SUBGRADE SOIL TYPES AND FOR LIGHT-, MEDIUM- AND HEAVY-DUTY TRAFFIC[a]

Int. Rate	Anal. Per. (yr)	Service Life (yr)	Price Rating	Annual Costs of Asphalt Cement Pavement and Shoulders per Mile ($)											
				R 5 Soil—Traffic Index			R 35 Soil—Traffic Index			R 50 Soil—Traffic Index			R 65 Soil—Traffic Index		
				8.5	10.0	11.5	8.5	10.0	11.5	8.5	10.0	11.5	8.5	10.0	11.5
3%	26	13	Low	3,530	4,170	4,720	3,150	3,760	4,230	2,900	3,760	4,230	2,580	3,060	3,530
			High	6,180	7,370	8,350	4,730	5,660	6,400	4,480	5,660	6,400	4,100	4,870	5,610
			Avg.	4,620	5,380	6,060	3,860	4,520	5,090	3,740	4,520	5,090	3,300	3,810	4,390
		18	Low	3,330	3,970	4,530	2,950	3,560	4,040	2,700	3,560	4,040	2,380	2,860	3,340
			High	5,890	7,080	8,070	4,440	5,370	6,120	4,190	5,370	6,120	3,810	4,580	5,330
			Avg.	4,390	5,150	5,820	3,630	4,290	4,850	3,510	4,290	4,850	3,070	3,580	4,150
	39	13	Low	3,300	3,810	4,240	3,010	3,490	3,860	2,810	3,490	3,860	2,570	2,930	3,310
			High	5,590	6,530	7,290	4,450	5,180	5,770	4,260	5,180	5,770	3,960	4,570	5,150
			Avg.	4,270	4,830	5,410	3,680	4,190	4,630	3,580	4,190	4,630	3,230	3,630	4,080
		18	Low	3,160	3,690	4,110	2,870	3,370	3,730	2,670	3,360	3,730	2,430	2,810	3,180
			High	5,350	6,300	7,060	4,210	4,950	5,540	4,020	4,950	5,540	3,720	4,340	4,920
			Avg.	4,060	4,660	5,220	3,470	3,980	4,440	3,370	3,980	4,440	3,020	3,420	3,890
6%	26	13	Low	4,440	5,330	6,080	3,920	4,760	5,400	3,570	4,760	5,400	3,140	3,780	4,430
			High	7,970	9,610	10,950	5,980	7,260	8,280	5,630	7,260	8,280	5,110	6,180	7,200
			Avg.	5,860	6,930	7,870	4,830	5,760	6,530	4,660	5,760	6,530	4,060	4,780	5,560
		18	Low	4,230	5,120	5,880	3,710	4,550	5,200	3,360	4,550	5,200	2,930	3,570	4,230
			High	7,670	9,320	10,640	5,680	6,970	7,970	5,330	6,970	7,970	4,810	5,890	6,890
			Avg.	5,620	6,670	7,610	4,590	5,500	6,270	4,420	5,500	6,270	3,810	4,520	5,300
	39	13	Low	4,240	5,010	5,690	3,790	4,520	5,100	3,490	4,520	5,100	3,110	3,670	4,250
			High	7,490	8,910	10,080	5,750	6,860	7,750	5,450	6,860	7,750	4,990	5,920	6,800
			Avg.	5,590	6,500	7,310	4,690	5,470	6,140	4,540	5,470	6,140	4,010	4,620	5,300
		18	Low	4,070	4,840	5,520	3,620	4,350	4,930	3,320	4,350	4,930	2,940	3,500	4,080
			High	7,190	8,620	9,790	5,450	6,570	7,460	5,150	6,570	7,460	4,690	5,630	6,510
			Avg.	5,350	6,260	7,080	4,450	5,230	5,910	4,300	5,230	5,910	3,770	4,380	5,070

[a]Analysis period 26 and 39 yr; service life of asphalt concrete pavement 13 and 18 yr, and of resurfacing, 13 yr; interest at 3 and 6%.

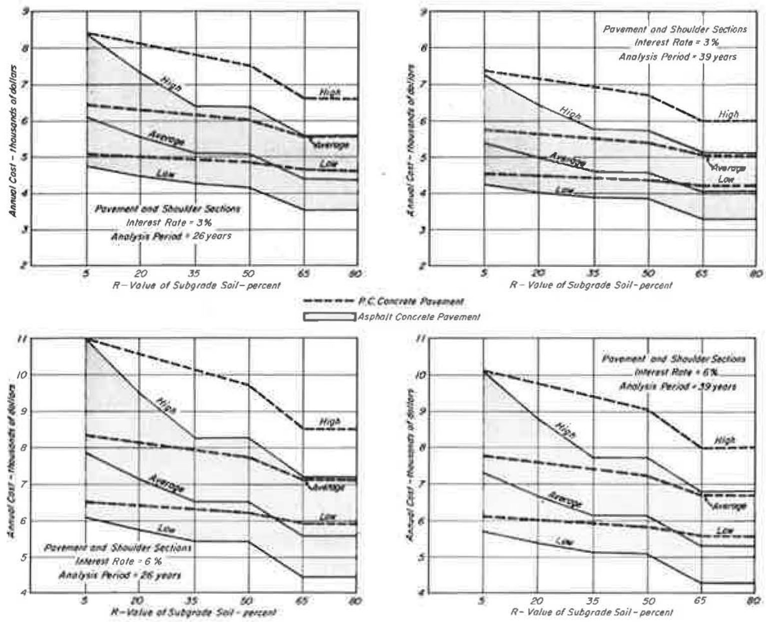

Figure 8. Annual costs per mile for 2-lane concrete and asphalt pavements and shoulders designed for six subgrade soil types and for heavy-duty traffic (TI = 8.5). Service life of the concrete pavements, 18 years, and of the asphalt pavements, 13 years; interest rates, 3 and 6%; analysis periods, 26 and 39 years.

of contract prices for paving projects in all parts of California and that the wide spread in annual costs may be attributed primarily to this geographic variation. The authors strongly advise that pavement cost comparisons be made, not by using statewide cost data, but on a project-by-project basis using cost data which apply to that project.

Effect of Soil Type and Traffic Loads on Annual Costs.—Another significant factor in a comparison of the annual costs of the two pavement types revealed by this study (Figs. 3 to 8) was the marked reduction in the annual costs of the flexible pavements with increased resistance (R-value) of the subgrade soil, the reduction in annual cost of rigid pavements being only one-third to one-half as much.

The greatest spread in annual costs for both pavement types was obtained for pavement sections designed for poor soils (R-value = 5) and for heavy-duty traffic for a 26-yr analysis period and a 6 percent interest rate. For these conditions the annual costs shown in Figure 4 for rigid pavements ranged from \$6,000 to \$10,100 per mile and for flexible pavements from \$6,000 to \$10,700.

The smallest spread in annual costs for both pavement types appears in Figure 6. It was obtained for pavement sections designed for excellent soils (R-value = 80), for light-duty traffic, and for annual costs computed for a 39-yr analysis period and a 6 percent interest rate. For the pavement section only, the rigid pavement annual costs ranged from \$3,600 to \$4,800 per mile, and the flexible pavement costs from \$2,000 to \$3,100 per mile. For the pavement and shoulder sections, the corresponding annual costs for rigid pavements ranged from \$4,700 to \$6,500 per mile and for flexible pavements from \$3,000 to \$4,800 per mile. Thus, for pavements designed for light-duty traffic and for excellent soil conditions, the annual costs of flexible pavements were 30 to 40 percent lower than the annual costs for rigid pavements.

Effect on Annual Costs of Including Shoulder Costs.—In Figures 3 to 6 the annual costs are shown for pavement sections only and for the combined pavement and shoulder sections for both pavement types. It should be noted in Table 3 and in the discussion of the structural design of the pavement and shoulder sections that the shoulders were and interest rates, is shown most effectively in chart form in Figures 3 to 8. In Figures 3 to 6 the annual costs for both rigid and flexible pavements are shown for six subgrade soil types and for light-duty and heavy-duty traffic for (a) only the pavement section, width 24 ft; and (b) the combined pavement and shoulder section, overall width 38 ft.

Figures 3 and 4 show the annual costs for an analysis period of 26 years, a service life of 26 years for the portland cement concrete pavements, a service life of 18 years for the asphalt concrete pavements, and interest rates of 3 and 6 percent. Figures 5 and 6 show annual costs computed for an analysis period of 39 years instead of the 26 years used in Figures 3 and 4. Figures 7 and 8 show the annual costs for service lives of 18 years for the asphalt concrete pavements instead of the 26- and 18-yr service lives used in Figures 5 and 6.

Effect of the High to Low Spread in Construction Costs on Annual Costs. --Figures 3 to 8 clearly show a surprising spread in annual costs (resulting from the high to low contract prices) for both types of pavements designed for identical soil and traffic conditions. They also show that there is a wide range of conditions in which annual costs of the two types of pavements overlap. In assembling the unit contract prices for the 155 paving projects in California, it was noted that in certain areas, as for example in Los Angeles County, where the unit prices for portland cement concrete pavement construction were low, the unit prices for asphalt concrete pavement construction were also low. Likewise, in other parts of the state, where the unit prices for portland cement concrete pavements were high, the unit prices for asphalt concrete were also high. While there was no attempt in this study to make a detailed analysis of unit contract prices within certain areas of the state to determine the extent to which the unit prices were very much lower for one type of pavement construction than for the other, there was evidence in the analysis of contract prices that a unit cost differential of this type existed which could influence the selection of pavement type. It is important to keep in mind that the unit prices used in this study were based on a study

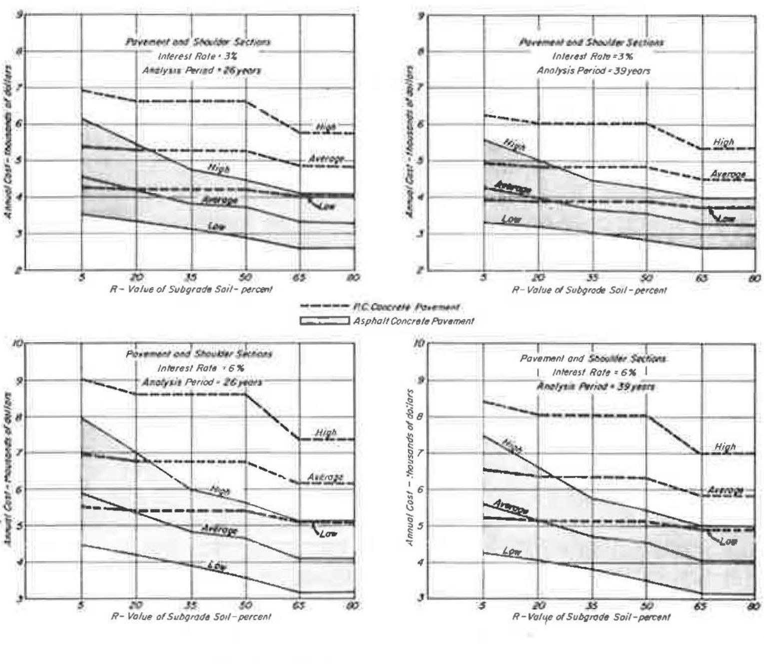

Figure 7. Annual costs per mile for 2-lane concrete and asphalt pavements and shoulders designed for six subgrade soil types and for light-duty traffic (TI = 8.5). Service life of the concrete pavements, 18 years, and of the asphalt pavements, 13 years; interest rates, 3 and 6%; analysis periods, 26 and 39 years.

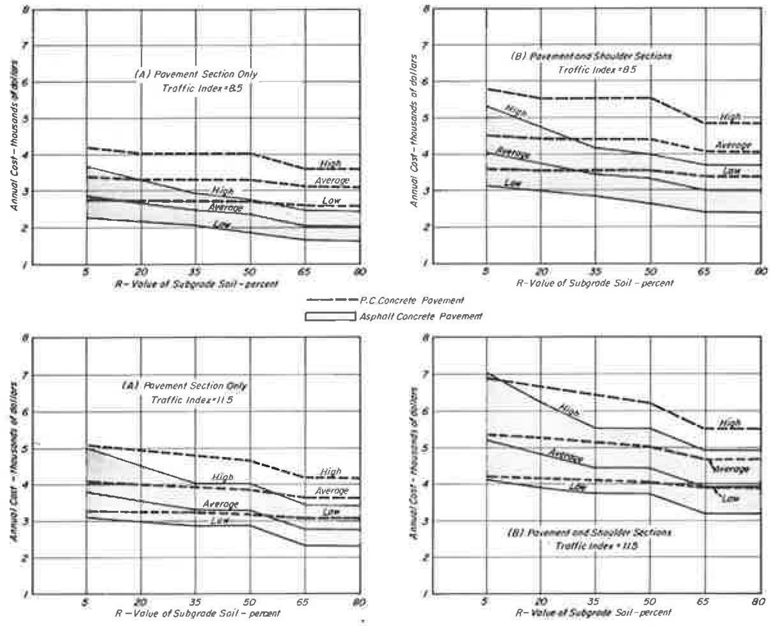

Figure 5. Annual costs per mile for (A) 2-lane concrete and asphalt pavements and (B) pavements and shoulders, designed for six subgrade soil types, for light-duty traffic (TI = 8.5) and heavy-duty traffic (TI = 11.5). Service life of the concrete pavements, 26 years, and of the asphalt pavements, 18 years; interest rate, 3 percent; analysis period, 39 years.

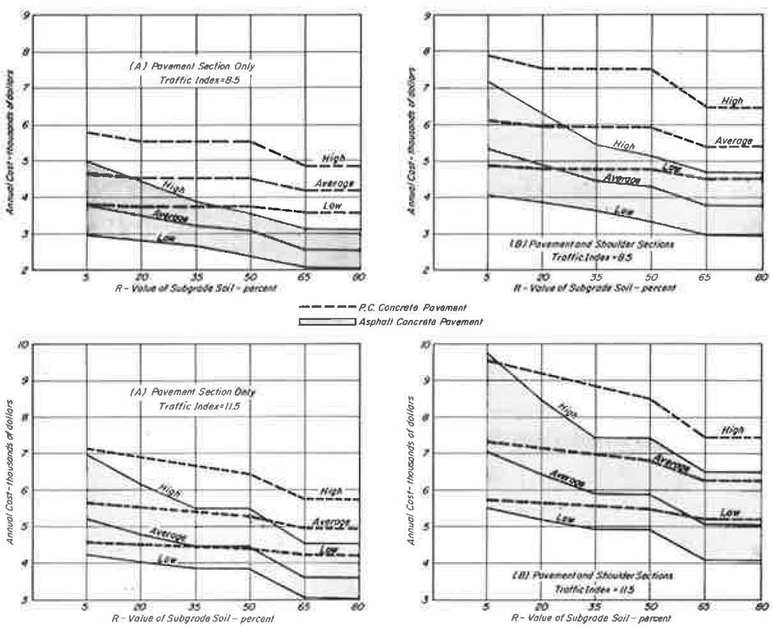

Figure 6. Annual costs per mile for (A) 2-lane concrete and asphalt pavements and (B) pavements and shoulders, designed for six subgrade soil types, for light-duty traffic (TI = 8.5) and heavy-duty traffic (TI = 11.5). Service life of the concrete pavements, 26 years, and of the asphalt pavements, 18 years; interest rate, 6 percent; analysis period, 39 years.

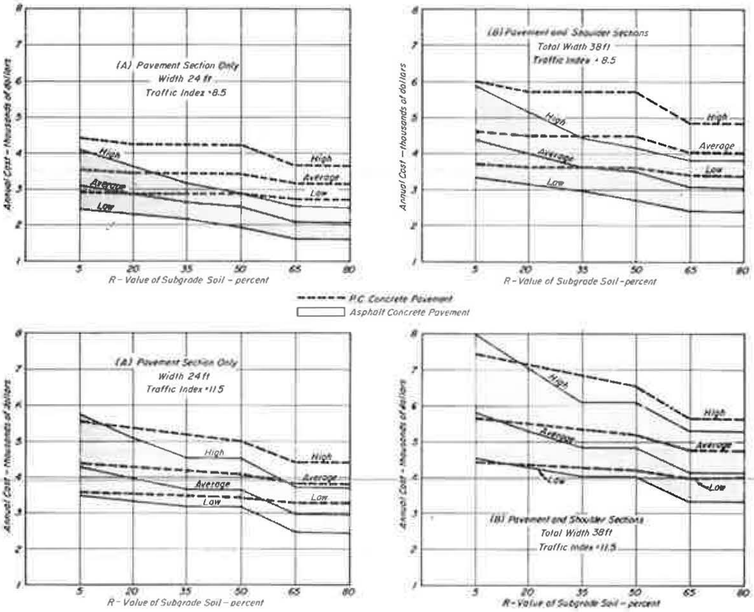

Figure 3. Annual costs per mile for (A) 2-lane concrete and asphalt pavements and (B) pavements and shoulders, designed for six subgrade soil types, for light-duty traffic (TI = 8.5) and heavy-duty traffic (TI = 11.5). Service life of the concrete pavements, 26 years, and of the asphalt pavements, 18 years; interest rate, 3%; analysis period, 26 years.

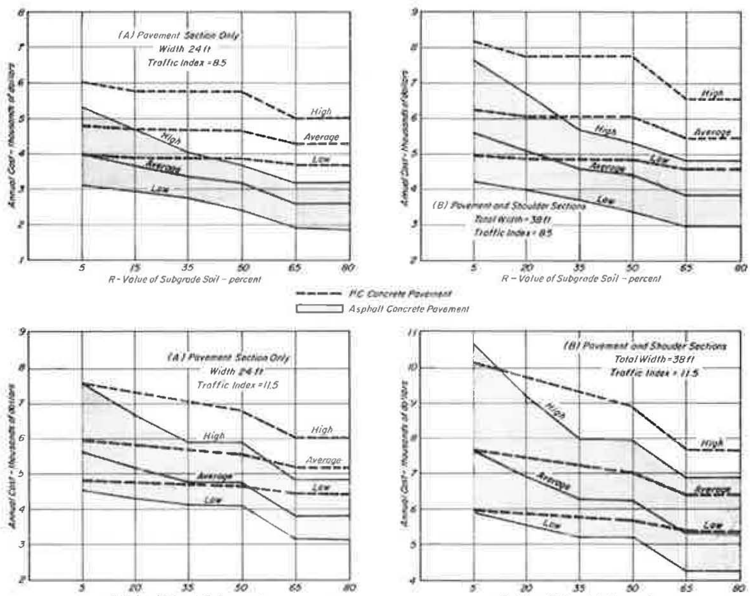

Figure 4. Annual costs per mile for (A) 2-lane concrete and asphalt pavements and (B) pavements and shoulders, designed for six subgrade soil types, for light-duty traffic (TI = 8.5) and heavy-duty traffic (TI = 11.5). Service life of the concrete pavements, 26 years, and of the asphalt pavements, 18 years; interest rate, 6%; analysis period, 26 years.

of time be taken fully into account. He recommended an analysis period of 40 years.

The California Division of Highways in their latest instructions stated that:

> An appropriate economic analysis period shall be chosen for each project based on the average life to the first resurfacing of concrete pavements in the area that served under comparable conditions. In general, the analysis period will range from 20 years upward based on present experience.

It is significant that for the evaluation of Federal public works projects analysis periods of 50 to 100 years are used and that for pavement cost comparisons the California Division of Highways uses analysis periods from 20 years upward. For this study, two periods of analysis were adopted: 26 years and 39 years. These fit the 26-yr service life of concrete pavements and the 13-yr service life of the asphalt concrete resurfacing adopted for this study.

Service Life of Initial Pavement Surfaces and of Resurfacings

As a part of the statewide highway planning surveys, California and many other states have cooperated with the U. S. Bureau of Public Roads in conducting road-life studies. In these studies, pavements as initially constructed are reported to have reached the end of their service life when they are resurfaced, reconstructed, abandoned or transferred from one system to another. A report (14) on the service life of highway surfaces published by the U. S. Bureau of Public Roads in 1956, presented data which showed that 88 percent of the high-type flexible and rigid pavements reached the end of their service life by reason of resurfacing or reconstruction (12 percent being abandoned or transferred). It is expected that future studies will show that the service lives of the initial pavement surface on modern freeways will be determined practically 100 percent on the basis of resurfacing requirements.

It is, of course, difficult to forecast the resurfacing requirements of the pavements for modern freeways which are being built according to the present-day high standards of pavement design and construction. However, the steadily increasing volumes and weight of commercial vehicles will very likely continue to contribute to increased pavement roughness, cracking, and rutting which will necessitate resurfacing with almost the same frequency as has been indicated by recent road-life studies in California and in many other states. It should be recognized also that higher speeds of all traffic on freeways today and in the future will demand a higher standard of pavement smoothness and riding quality than in the past, in order to provide the desired driving safety and comfort.

To meet future pavement smoothness requirements, the authors adopted two frequencies for resurfacing for each pavement type, one of which was slightly higher and the other lower than the frequency indicated by road-life studies in California and as reported in 1956 by the U. S. Bureau of Public Roads (14) for high-type pavements throughout the United States.

Initial pavement surface lives adopted for this study were 18 years and 26 years for rigid pavements and 13 and 18 years for flexible pavements. For both pavement types, resurfacing cost computations are based on resurfacing with asphalt concrete with a service life of 13 years.

ANNUAL COSTS OF RIGID AND FLEXIBLE PAVEMENTS

The annual costs of 48 rigid and flexible pavement and shoulder sections computed for a two-lane width of roadway and a length of one mile, in terms of the variables previously discussed in this paper, are shown in Figures 3 to 8 and in Tables 15 to 20.

The influence on the annual costs of such variables as the initial construction costs in terms of the various unit contract prices, resurfacing costs, maintenance costs, the service lives of the initial surfacing and of the resurfacing, the analysis periods

Extensive field observations by the senior author during the past 15 years indicate that the California Division of Highways has achieved an outstanding record of pavement performance with very few projects constructed during the past 10 years where the average annual maintenance costs have exceeded $1,000 per mile. However, in the ITTE road roughness tests on pavements in all parts of California conducted by the senior author, several projects were encountered of both asphalt and portland cement concrete paving where extensive failures had developed requiring annual maintenance costs exceeding $1,000 per mile. Investigation of these failures by the Division of Highways, Materials and Research Department, indicated that they were caused by the use of faulty paving materials and by improper construction. The very high maintenance costs for these pavements were not considered to be representative of the maintenance costs of pavements built today or in the future and were therefore not used in this study.

As with resurfacing costs, a 2 percent price-trend factor was included in maintenance costs to take into account the expected long-range trend of increased costs for paving materials and for safeguards to prevent traffic delays and accidents.

Interest Rates

The annual costs of the two pavement types were computed on the basis of two interest and discount rates: 3 percent and 6 percent. The 3 percent rate was adopted as a typical minimum risk-free interest rate recommended by the committee in the Federal Inter-Agency report (11) on the basis of the following criteria:

> The minimum interest rate appropriate for use in project evaluation is the risk-free return expected to be realized on capital invested in alternate uses (for Federal public works projects) .... This rate is the projected average rate of return on such relatively risk-free investments as long-term Government bonds.
>
> With limited amounts of resources available for capital investment, the interest cost of investing these resources in water development (or similar Federal public works projects) is measured by the rate of return that would be realized if the capital were invested in other uses of comparable risk and duration.

Representatives of the Department of Commerce, in commenting on the report, recommended that for Federal power projects an interest rate of 4½ percent, which included a risk component, should be used. For this study, a 6 percent rate was adopted as representative of an interest rate with a risk component.

Analysis Periods

One of the most important features in the development of freeways with full control of access today is their permanence. Modern freeways are built to high design standards both as to horizontal and vertical alignment and as to structural adequacy. Present indications are that they should continue to provide satisfactory service for many years to come. However, as Baldock stated (4):

> Future technological changes (in the next 40 years) may make present-day roads obsolete and render more attractive a different type of transportation investment. There is no present indication that such changes will jeopardize the billions of dollars now being invested in roads. However, discretion requires that present and future beneficiaries carry the requisite costs to retire the investment within a reasonable period of time.... This period of time may be termed the analysis period.

Baldock recommended that the analysis period should be long enough to extend well past the first resurfacing period in order that all annual costs over a fairly long period

TABLE 18

ANNUAL COSTS OF A 2-LANE MILE OF ASPHALT CONCRETE PAVEMENT AND SHOULDERS FOR NINE TYPICAL DESIGN SECTIONS FOR 39-YR ANALYSIS PERIOD[a]

Design Section			Contract Price Rating	Annual Costs of Pavement and Shoulders for 39-Yr Analysis Period								
No.	R-Value of Soil	Traffic Index		Initial Construction Costs ($)		Resurfacing Costs ($)		Salvage Value (-) ($)		Maintenance Costs ($)	Total Annual Costs per Mile ($)	
				3%	6%	3%	6%	3%	6%		3%	6%
1	R 5	8.5	Low	1,960	2,990	800	620	120	60	520	3,160	4,070
			High	3,840	5,860	1,160	900	170	90	520	5,350	7,190
			Avg.	2,730	4,160	950	740	140	70	520	4,060	5,350
2		10.0	Low	2,470	3,760	820	620	120	60	520	3,690	4,840
			High	4,770	7,280	1,180	910	170	90	520	6,300	8,620
			Avg.	3,330	5,070	950	740	140	70	520	4,660	6,260
3		11.5	Low	2,890	4,420	820	640	120	60	520	4,110	5,520
			High	5,530	8,450	1,180	910	170	90	520	7,060	9,790
			Avg.	3,860	5,880	980	750	140	70	520	5,220	7,080
7	R 35	8.5	Low	1,670	2,540	800	620	120	60	520	2,870	3,620
			High	2,700	4,120	1,160	900	170	90	520	4,210	5,450
			Avg.	2,140	3,260	950	740	140	70	520	3,470	4,450
8		10.0	Low	2,150	3,270	820	620	120	60	520	3,370	4,350
			High	3,420	5,230	1,180	910	170	90	520	4,950	6,570
			Avg.	2,650	4,040	950	740	140	70	520	3,980	5,230
9		11.5	Low	2,510	3,830	820	640	120	60	520	3,730	4,930
			High	4,010	6,120	1,180	910	170	90	520	5,540	7,460
			Avg.	3,080	4,710	980	750	140	70	520	4,440	5,910
13	R 65	8.5	Low	1,230	1,860	800	620	120	60	520	2,430	2,940
			High	2,210	3,360	1,160	900	170	90	520	3,720	4,690
			Avg.	1,690	2,580	950	740	140	70	520	3,020	3,770
14		10.0	Low	1,590	2,420	820	620	120	60	520	2,810	3,500
			High	2,810	4,290	1,180	910	170	90	520	4,340	5,630
			Avg.	2,090	3,190	950	740	140	70	520	3,420	4,380
15		11.5	Low	1,960	2,980	820	640	120	60	520	3,180	4,080
			High	3,390	5,170	1,180	910	170	90	520	4,920	6,510
			Avg.	2,530	3,870	980	750	140	70	520	3,890	5,070

[a]Interest at 3 and 6%; service life of asphalt cement pavement = 18 yr; service life of resurfacings = 13 yr.

per mile. For the asphalt concrete pavements with service lives of 13 and 18 years and for analysis periods of 26 and 39 years, the average annual maintenance costs adopted for this study were $450 and $520 per mile, respectively.

These maintenance costs were established in accordance with the California Division of Highways Maintenance Manual of Instructions (12) where maintenance is defined as the restoration and repair of both surface and base within the entire area that is improved for vehicular use. Pavement repair in California is regarded as maintenance if the blanket is not more than 1 in. thick and 500 ft long. Maintenance in excess of 500 ft is financed from construction funds. Maintenance does not include reconstruction of the pavement or shoulders, which is also financed from construction funds.

The maintenance costs for this study were established on the basis of statewide maintenance costs of primary state highways in California, adjusted for a 2 percent price-trend factor. As in the case of the resurfacing costs used in this study, no distinction was made in the maintenance costs for the variations in the volumes and weight of traffic and in the type of subgrade soil. It was assumed that the structural design of all the sections was entirely adequate to serve the traffic, and that available data do not warrant the introduction of variable maintenance costs.

The annual maintenance costs for the two pavement types adopted for this study are higher than the average annual maintenance costs given in the report on pavement economics by the Stanford Research Institute (6). They are lower than the average annual maintenance costs for pavements in California given in the Portland Cement Association Report (13) in which extensive pavement maintenance cost data are presented as a part of the comprehensive engineering analysis and evaluation of the SRI report on pavement economics.

TABLE 16

ANNUAL COSTS OF A 2-LANE MILE OF ASPHALT CONCRETE PAVEMENT AND SHOULDERS FOR NINE TYPICAL DESIGN SECTIONS FOR A 26-YR ANALYSIS PERIOD[a]

Design Section			Contract Price Rating	Annual Costs of Pavement and Shoulders for 26-Yr Analysis Period								
No.	R-Value of Soil	Traffic Index		Initial Construction Costs ($)		Resurfacing Costs ($)		Salvage Value (-) ($)		Maintenance Costs ($)	Total Annual Costs per Mile ($)	
				3%	6%	3%	6%	3%	6%		3%	6%
1	R 5	8.5	Low	2,500	3,440	540	440	160	100	450	3,330	4,230
			High	4,890	6,730	780	640	230	150	450	5,890	7,670
			Avg.	3,480	4,770	650	530	190	130	450	4,390	5,620
2		10.0	Low	3,140	4,330	540	440	160	100	450	3,970	5,120
			High	6,080	8,370	780	650	230	150	450	7,080	9,320
			Avg.	4,240	5,820	650	530	190	130	450	5,150	6,670
3		11.5	Low	3,690	5,080	550	450	160	100	450	4,530	5,880
			High	7,060	9,700	790	650	230	160	450	8,070	10,640
			Avg.	4,910	6,760	650	530	190	130	450	5,820	7,610
7	R 35	8.5	Low	2,120	2,920	540	440	160	100	450	2,950	3,710
			High	3,440	4,740	780	640	230	150	450	4,440	5,680
			Avg.	2,720	3,740	650	530	190	130	450	3,630	4,590
8		10.0	Low	2,730	3,760	540	440	160	100	450	3,560	4,550
			High	4,370	6,020	780	650	230	150	450	5,370	6,970
			Avg.	3,380	4,650	650	530	190	130	450	4,290	5,500
9		11.5	Low	3,200	4,400	550	450	160	100	450	4,040	5,200
			High	5,110	7,030	790	650	230	160	450	6,120	7,970
			Avg.	3,940	5,420	650	530	190	130	450	4,850	6,270
13	R 65	8.5	Low	1,550	2,140	540	440	160	100	450	2,380	2,930
			High	2,810	3,870	780	640	230	150	450	3,810	4,810
			Avg.	2,160	2,960	650	530	190	130	450	3,070	3,810
14		10.0	Low	2,030	2,780	540	440	160	100	450	2,860	3,570
			High	3,580	4,940	780	650	230	150	450	4,580	5,890
			Avg.	2,670	3,670	650	530	190	130	450	3,580	4,520
15		11.5	Low	2,500	3,430	550	450	160	100	450	3,340	4,230
			High	4,320	5,950	790	650	230	160	450	5,330	6,890
			Avg.	3,240	4,450	660	530	190	130	450	4,150	5,300

[a]Interest at 3 and 6%; service life of asphalt cement pavement = 18 yr; service life of resurfacing = 13 yr.

TABLE 17

ANNUAL COSTS OF A 2-LANE MILE OF PORTLAND CEMENT CONCRETE PAVEMENT AND SHOULDERS FOR NINE TYPICAL DESIGN SECTIONS FOR 39-YR ANALYSIS PERIOD[a]

Design Section			Contract Price Rating	Annual Costs of Pavement and Shoulders for 39-Yr Analysis Period						
No.	R-Value of Soil	Traffic Index		Initial Construction Costs ($)		Resurfacing Costs ($)		Maintenance Costs ($)	Total Annual Costs per Mile ($)	
				3%	6%	3%	6%		3%	6%
1	R 5	8.5	Low	2,640	4,040	620	450	370	3,630	4,860
			High	4,490	6,850	960	690	370	5,820	7,910
			Avg.	3,380	5,170	810	580	370	4,560	6,120
2		10.0	Low	3,160	4,830	630	450	370	4,160	5,650
			High	5,360	8,190	960	690	370	6,690	9,250
			Avg.	4,070	6,210	810	580	370	5,250	7,160
3		11.5	Low	3,230	4,920	630	460	370	4,230	5,750
			High	5,600	8,540	960	700	370	6,930	9,600
			Avg.	4,190	6,390	820	590	370	5,380	7,350
7	R 35	8.5	Low	2,590	3,950	620	450	370	3,580	4,770
			High	4,250	6,490	960	690	370	5,580	7,550
			Avg.	3,270	4,990	810	580	370	4,450	5,940
8		10.0	Low	3,050	4,650	630	450	370	4,050	5,470
			High	4,900	7,470	960	690	370	6,230	8,530
			Avg.	3,830	5,850	810	580	370	5,010	6,800
9		11.5	Low	3,110	4,750	630	460	370	4,110	5,580
			High	5,140	7,830	960	700	370	6,470	8,900
			Avg.	3,950	6,030	820	590	370	5,140	6,990
13	R 65	8.5	Low	2,420	3,680	620	450	370	3,410	4,500
			High	3,550	5,410	960	690	370	4,880	6,470
			Avg.	2,920	4,450	810	580	370	4,100	5,400
14		10.0	Low	2,880	4,380	630	450	370	3,880	5,200
			High	4,190	6,400	960	690	370	5,520	7,460
			Avg.	3,480	5,310	810	580	370	4,660	6,260
15		11.5	Low	2,880	4,380	630	460	370	3,880	5,210
			High	4,190	6,400	960	700	370	5,520	7,470
			Avg.	3,480	5,310	820	590	370	4,670	6,270

[a]Interest at 3 and 6%; service life of portland cement concrete pavement = 26 yr; service life of resurfacing = 13 yr.