WA-RD-76-14
AL REPORT

OMIC ANALYSIS OF ROADWAY OCCUPANCY FOR FREEWAY PAVEMENT MAINTENANCE AND REHABILITATION

Prepared for
FEDERAL HIGHWAY ADMINISTRATION
Offices of Research & Development
Washington, D.C. -20590

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Technical Report Documentation Page

1. Report No.
FHWA-RD-76-14

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
ECONOMIC ANALYSIS OF ROADWAY OCCUPANCY FOR FREEWAY PAVEMENT MAINTENANCE AND REHABILITATION
Vol. 1 - Final Report

5. Report Date
October, 1974

6. Performing Organization Code

7. Author(s)
B. C. Butler, Jr.

8. Performing Organization Report No.

9. Performing Organization Name and Address
Byrd, Tallamy, MacDonald and Lewis
Division of Wilbur Smith and Associates
2921 Telstar Court
Falls Church, Virginia 20590

10. Work Unit No. (TRAIS)
FCP-35E1012

11. Contract or Grant No.
DOT-FH-11-8132

12. Sponsoring Agency Name and Address
Office of Research and Development
Federal Highway Administration
U.S. Department of Transportation
Washington, D.C. 20590

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code
S 0 6 2 8

15. Supplementary Notes
FHWA Contract Manager: J. V. Boos (HRS-41)

16. Abstract

A program (manual and computerized) was developed to perform an economic analysis of premium pavements (reduced maintenance requirements). Pavement maintenance costs were determined in terms of impacts on motorists (users) and the general public (non-users) of freeways.

Volume I - Final Report - This volume provides a complete description of the scope, approach, and results of evaluating the economic impact of roadway maintenance crew occupany, taking into account motor vehicles operating cost, value of time, accidents, and pollution under various freeway traffic conditions. The assessments and conclusions are based upon previous state-of-the-art and a study of field data.

This volume is the first of a three volume series. The others in the series are:

Vol. No.	FHWA. No.	Short Title
2	76-15	Users Manual
3	76-16	Program Documentation

17. Key Words
Pavement Design, Highway Maintenance, Economics, Traffic, Vehicle Operation Costs, Accident Cost, Value of Time, Pollution, Maintenance Models, Simulation

18. Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	291	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGEMENT

The research study covered by this report was conducted by the Byrd, Tallamy, MacDonald and Lewis Division of Wilbur Smith and Associates. The principal investigator was Bertell C. Butler, Jr. Others making contributions to the study included Stephen W. Hopkins who assisted in all phases of the study and contributed substantially in the development of the computer program; L. G. Byrd, who provided guidance in the development of the maintenance module; Robley Winfrey, who critiqued the approach to developing vehicle operation cost, and made available information on vehicle operating characteristics; Ross Maxwell, who directed field data gathering efforts in California, and other firm members who gave suggestions and provided assistance during the conduct of the research.

The author wishes to thank the state highway staff members in California, Maryland, and Virginia for their cooperation in providing notice of maintenance occupancy conditions and data on traffic related to roadway occupancy locations.

Special thanks are extended to Mr. James Boos of the Federal Highway Administration who, as project manager, provided invaluable assistance in contacts with Federal and State highway staff members.

Other Federal Highway Administration personnel who made contributions to the study include Tom Pasko and Dick McComb, Office of Research and Development; Ed Evans, Richard Murphy and James Robertshaw, Computer Services Division, and Perry Kent, Program Management Division.

PREFACE

Report Contents

"An Economic Analysis of Roadway Occupancy for Freeway Pavement Maintenance and Rehabilitation" is contained in three volumes. This is the result of work accomplished under a Federally Coordinated Research Program, Project 5E, Premium Pavements for "Zero Maintenance," during the period of July 1973 to May 1975.

Volume I, Final Report, provides a complete description of the scope, approach, and results of evaluating the economic impact of roadway maintenance crew occupancy, taking into account motor vehicle operating cost, value of time, accidents, and pollution under various freeway traffic conditions. The assessments and conclusions are based upon previous state-of-the-art and study of field data.

Volume II, Users Manual, presents the results of the study as a users manual with a systems approach to pavement design, which evaluates environmental, operational performance and serviceability factors for alternative pavements under a variety of rehabilitation and maintenance strategies. The presentation is in two parts: The first is the Algebraic Users Manual, for hand computations. The second is the User Manual for Program EAROMAR (Economic Analysis for Roadway Occupancy for Maintenance and Rehabilitation) which gives a detailed description of the format and coding for all required input and a general description of the optional input to modify the impacts for local needs.

Volume III, Program Documentation, contains a complete description of the internal variable and computations for the computer program EAROMAR, and thus is the basis for any future program modifications. The format and coding for all inputs are described in detail. One change to the program has been made by FHWA, which is documented in this Volume. This modification incorporates an inflation rate of 10 percent in present worth computations.

Report Applications

High traffic volumes, heavy loads, and weathering on existing pavement designs cause accelerated damage and early deterioration. Maintenance operations required to keep these highway facilities serviceable create a conflict with the motorist causing delays, and increasing pollution and accident opportunities. These repairs are: (1) costly due to the extensive traffic control required, (2) limited to between peak hour periods to avoid exceeding the traffic volume capacity, and (3) difficult to perform and often temporary due to problems in mobilizing the work crew. Thus the elimination of these impacts results in reduced highway maintenance expenditures and higher levels of safety, economy and convenience to the user.

The FHWA has determined that one solution to the difficulties associated with highway maintenance operations is to produce a "premium pavement" which reduces maintenance requirements. The savings derived from direct maintenance expenditures and motorist costs over the life of the pavement could be invested in constructing a "premium pavement" as compared to existing designs.

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INTRODUCTION

Existing pavement design on freeways is subject to accelerated deterioration due to weathering, heavy loads and high traffic volumes. This deterioration creates a need for maintenance early in the life of the pavement and results in disruption of traffic by maintenance occupancy forces. Such maintenance is costly due to the extensive traffic control needed to protect both maintenance crews and motorists. Scheduling of these occupancy periods must occur during off peak hours to avoid exceeding volume capacity. Also, maintenance crew job site movements are hampered by limited access and high traffic speeds. Maintenance performed under these conditions must frequently be repeated because limited time results in temporary or hasty repairs which are costly. These occupancy periods also cause conflicts with the motorist and in turn affects motorist operating costs, delays and increases potential for accidents. Finally, the general slowing of traffic generates increased levels of pollution. The elimination of these costs and impacts can result in reduced highway maintenance expenditures and higher levels of safety, economy and convenience to the highway user.

One means of minimizing these difficulties associated with freeway maintenance is to produce a pavement, which can be referred to as a "premium pavement," requiring less maintenance or no maintenance. This subsequent reduction in direct maintenance activities will in turn reduce maintenance expenditures, motorist costs, i.e., operation, time, and accidents. These savings could justify the increased costs of constructing this, so called, "premium Pavement."

An adequate economic analysis of the cost of maintenance, rehabilitation and motorist impacts as they relate to a "premium pavement" must take into consideration the relationship of a multitude of quantifiable costs for a wide range of pavement design strategies and therefore a systems approach appears proper. The systems approach accomplishes this through allocation of present and future cash flow which are quantified and converted to present worth in evaluating a range of pavement design strategies over a pavement's life. A wide range of pavement designs and maintenance strategies have been acknowledged to exist among the 50 State highway departments and therefore the objective sought in this research effort were directed primarily to developing motorist costs common to all States.

Specifically, the objective of this project was the development of motorist-related data inputs for currently available systems analysis models for pavement design as a preliminary effort in the development of economic warrants for the use of premium pavements. The economic analysis will encompass vehicle operating costs, delays to drivers and passengers, air pollution, and accidents related to maintenance operations.

Scope

This study was to draw on existing system analysis models which could be used for analyzing highway maintenance, but any model selected was to be modified as necessary to insure that it is easily adaptable to the needs of the 50 State highway departments.

The maintenance predicted in the model was to be limited to activities related to rigid and flexible pavement systems. Information identified as being relevant to the model included highway vertical and horizontal alignment, vehicle trip purpose and occupant income level, speed profiles, traffic volume, traffic composition and hourly distribution, accidents, detour lengths, and lane closure configurations.

The model was to accommodate 4-, 6-, and 8-lane freeways. In the determination of values for time, the use of the procedure and information provided in the SRI research report "The Value of Time Saved by Trip Purpose," (27) was incorporated into the study.

Existing Maintenance Models

Two formal literature searches were made to identify system models related to pavement maintenance. One search was through the Highway Research Information Service and the second was through the National Technical Information Service.

The principal system analysis models for pavements which were identified as presently being developed were the following:

A. The Texas Transportation Institute, University of Texas and Texas Highway Department, Judson, McCullough, et al. (1-10)

B. The Massachusetts Institutes of Technology, Moavenzadeh, et al. (11-19)

C. The Australian Commonwealth, Brueau of Roads, Both, Lock, Delaney, et al. (20)

D. The Ontario Department of Transportation and Communications, Phang, et al. (21-25)

Each of these models address highway maintenance and rehabilitation to some degree. Other pavement design systems have been reported which consider rehabilitation but not maintenance. All of these studies have been reviewed and evaluated by one or another of the above-listed agencies in connection with their system analysis models.

The Texas group has given major emphasis to evaluating roadway occupancy impact on the user as part of the total economic evaluation of roadway design. However, the impact is limited to rehabilitation occupancy. The rehabilitation cycles are based on pavement performance predictions to some specified minimum present serviceability rating. Both the initial design and the rehabilitation design are considered in the analysis. The prediction of a terminal Pavement Serviceability Index (PSI) involves the evaluation of projected traffic loadings and the subgrade condition for a given pavement design. Maintenance requirements are based on the model presented in NCHRP-42 (26). The model predicts total annual pavement and shoulder maintenance requirements as a function of pavement age and days of freezing weather.

The MIT group has emphasized the uncertainties and variabilities associated with the physical characteristics of a pavement system and of the environment to which the pavement is subjected. These uncertainties, expressed in terms of probabilistic distributions, are used in a series of analytical models to predict three modes of damage progression (rut depth, slope variance, cracking) over time for various pavement designs. A probability distribution for the pavement condition (PSI), in terms of the AASHO present serviceability equation, is determined using predictions of the three damage parameters and their computed variances. This distribution is used in the computation of PSI value on an annual basis.

Polynominal regressions were computed for the data developed in the AASHO road test to produce equations which predict mean rut depth and the area of patching and cracking as a function of PSI. The MIT model predicts maintenance requirements as a function of these two damage components. The patching quantity is based on the difference between the patching and cracking areas predicted in two adjacent years. It also is related to a maintenance level which specifies the percent of available patching which will be done. Similar assumptions are made for sealing the patching and cracking area. Also, assumptions are made on filling ruts with patching material.

The MIT group assumes a direct relationship between the level of maintenance and the pavement condition (PSI) and adjust each year's predicted PSI through a feedback process.

The quantity of maintenance is costed using standardized estimates of labor, equipment and material for each unit of maintenance required.

The work done in Australia was directed toward evaluating the consequences of alternate road improvements and therefore is a highway economic evaluation model. However, the maintenance for pavement surfaces is modeled as a function of the age of the sealed surface, the surface area and traffic. The model is based on historical records of actual maintenance cost on well-maintained roads together with estimates of typical surface age and traffic.

The pavement model system presented by Ontario mentions the necessary elements, i.e., delay cost to user associated with resurfacing and maintenance and maintenance costs. The delay costs are not used but reference is made to work done by the Road Research Laboratory. Maintenance costs are assumed to increase with pavement age and only rough estimates were used in examples of the model.

Most of the models reviewed concentrate on predicting resurfacing cycles over the life of the pavement based on some measure of service to the user. Only Texas included an analysis of user cost associated with rehabilitation. MIT has the only model to predict specific maintenance requirements, i.e., patching, sealing, rut filling. Further, these quantified requirements are related to the pavement design. The other models predict general surface maintenance and apply to any high-type pavement surface.

It was concluded that none of the existing models would satisfy the objectives sought in this project. The existing models, with the exception of the MIT model, predict a single all-encompassing pavement maintenance requirement, usually in monetary terms. The MIT model predicts patching for bituminous pavements only and as a function of the pavement's present serviceability index.

Approach

An effective evaluation of the economic impact of roadway occupancy on the highway motorist requires a good estimate of the magnitude of work required by the maintenance forces over the life of the pavement. This estimate should embrace quantified estimates of workload for a range of activities. Further, the work required must be translated into hours of required roadway occupancy.

The forecast of workload should be related to the pavement design, its age and the factors it will be subjected to over its life. These include traffic loadings, climatic factors and maintenance levels.

Without detailed models, the only analysis possible is that between general levels of maintenance, i.e., existing maintenance levels versus no maintenance or a percent reduction in existing overall levels. As envisioned, the approach most likely to be taken in developing a premium pavement is to consider how to eliminate or reduce specific maintenance activities. For example, eliminate blow-ups or joint sealing or pavement patching. If the savings in maintenance and user costs exceeds the increased construction costs associated with the premium pavement which eliminates the maintenance, then an economic warrant for the construction of the premium pavement has been established.

Data or models permitting the prediction of annual levels of specific pavement maintenance activity do not exist. However, many highway agencies are presently in the process of developing or implementing either or both pavement management and maintenance management systems. In the future, these systems can be expected to generate the data needed to develop the required maintenance activity models sought for this project.

Until these models are available, a series of interim models will be developed. These will be based on available, though limited data, but will allow for the development of a comprehensive structuring of a systems analysis model for predicting maintenance requirements.

Once an annual workload has been predicted for an activity, it must be translated into specific hours of roadway occupancy. These hours of roadway occupancy determined needed to be established in terms of the days of each hour of occupancy. These hours will vary widely between State agencies, depending on a number of factors, which include:

1. The time spent at each worksite
2. The net hours of continuous time available for closing lanes of the freeway
3. The hours that a work crew is permitted to work
4. The length of the roadway work zone and the concentration of work within the work zone.

It was determined that variations in these factors could be handled by allowing them to be input into a program which would simulate the performance of work on the roadways. In this way the hours of roadway occupancy determined would be responsive to local practices and changes over time could readily be accumulated to update the program.

Individual agencies can make use of activity performance standards to develop productivity rates at worksites and to cost the activity.

The economic impact of a roadway closure on the highway motorist includes an evaluation of the change in:

1. Vehicle operation costs
2. Time costs
3. Accident costs
4. Pollution levels.

For a given roadway, vehicle operation costs will be a function of speed, speed changes, traffic volume and composition. A data collection program was planned and implemented to develop data on speeds and speed changes at maintenance worksites on 4-, 6-, and 8-lane freeways. This data was used in the development of models which could be used to predict vehicle average speeds under a variety of roadway lane closure conditions. Traffic volumes must be specified by the user of the economic analysis developed in this study. Traffic composition is built into programming developed for the analysis but can optionally be specified by the user.

The vehicle operation parameters which make up vehicle operation costs are principally:

1. Fuel consumption
2. Tire wear
3. Oil consumption
4. Maintenance expenses
5. Depreciation.

To insure that the program being developed for the economic analysis of roadway occupancy for maintenance and reconstruction could be readily updated, each of the five operation parameters was modeled. In this way current unit costs inputs for fuel, tires, oil, maintenance, and vehicles could be used in the analysis.

The study scope required that the time costs be evaluated using the procedures developed by SRI (27). This requires traffic volume information by trip purpose. To accommodate this requirement, it was decided that an hourly volume matrix defining the following seven trip purposes would be incorporated into the program by roadway direction:

1. Work trips
2. Personal business trips
3. Social recreation trips

4. School trips
5. Vacation trips
6. Commercial vehicle trips
7. Total trips.

The value of time routine developed by SRI also requires a measure of the increment of time loss per vehicle. This is based on the average time loss associated with all vehicles in a given hour of the day.

HIGHWAY MAINTENANCE MODULE

Maintenance Workload Models

One of the sources of data used for developing models for this project was developed in conjunction with NCHRP Report No. 42[26]. In this NCHRP study No. 14-1, maintenance activity data was developed by the consultant on 28 sections of interstate highways in five regions of the country. Seven different categories of pavement maintenance were specifically identified and reported on by personnel working for each of the agencies maintaining the sections. A form developed by the consultant was used for reporting and the reported information was thoroughly screened and validated to insure its accuracy. Therefore, it was felt that this information could be relied on in developing models or relationships.

The reporting form developed by the consultant accounted for man-hours by class of labor, equipment hours or mileage (as was appropriate) for a range of equipment classifications, and the quantity of material and its unit cost. The accounts established for the purpose of collecting data on the maintenance of pavements were defined as follows:

A. Routine Roadway Surface Operations

1. Patching -- All permanent and temporary patching on both concrete and bituminous pavements.
2. Joint and crack filling -- All work associated with joint and crack filling of a pavement including cleaning and cutting wells not including any work associated with the edge crack

between the pavement and the shoulder which should be charged to another account number.

3. Other costs -- All routine work done on the pavement surface which is not included under Items 1 and 2.

B. Special Roadway Surface Operations

1. Mudjacking and undersealing -- All work associated with raising concrete slabs by pumping material under the slab or any work associated with filling voids under either rigid or flexible type pavements regardless of the type of material used.

2. Bituminous treatment -- All work where bituminous liquids are placed on a pavement surface not including joint or crack filling and regardless of whether aggregates are used to cover the bituminous liquid. Covering excess bituminous materials with sand or aggregate also is included under this item.

3. Resurfacing (bituminous less than 3/4" thick) -- All work where a bituminous mix is used on pavement surface not including items normally included under patching and where final thickness of the bituminous material does not exceed 3/4".

4. Other costs -- All special work done on the pavement surface which is not included under items 1, 2, and 3.

The data which was summarized from the daily reports developed for the NCHRP 14-1 study for each of the above delineated activities was tabulated by man-hours. An examination of the total man-hours associated with each activity revealed the following distribution of work. Under A-1, patching, 57.2% of the total man-hours were invested. Under A-2, sealing joints, 26.7% of the total man-hours were invested. Therefore, for all pavement types, these two categories accounted for approximately 84% of the total investment in man-hours. Other categories where extensive work was reported included B-1, mudjacking and undersealing, where 13% of the man-hours invested in these sections was expended. For the overlay and bituminous sections, 26.7% of the man-hours were invested in Item B-2, bituminous treatment. The remainder of the activity on the sections monitored in the NCHRP study were invested in maintenance resurfacing and in the "other" cost account categories, A-3 and B-4.

The only maintenance activity data common to essentially all test sections in the 14-1 study was the pavement patching. The other activities were scattered randomly to sections and therefore could not be used as a basis for model development. They were useful in providing a subjective assessment of the relative weightings to be associated with each activity in the total maintenance requirement.

Pavement Patching

The major pavement maintenance activity is pavement patching. This is revealed in the above statistics. Therefore, a comprehensive analysis was made of data available from 14-1 for the purpose of developing pavement patching models. The data was examined in three groups and three investment categories. The groups were concrete pavements, bituminous and overlay pavements, and all pavements. The categories were man-hours, total costs, and material cost. A series of independent variables which were thought to have a possible influence on the magnitude of pavement patching were identified. These variables were as follows:

1. Average annual daily traffic volume per lane
2. Pavement age and age^2
3. 18-kip axle loadings per lane
4. Accumulated 18 kip axle loadings per lane over the life of the pavement (life being pavement age)
5. Number of days when the maximum daily temperature was below 32^oF

The selection of these variables was based on the original analyses made of the total data where a single pavement model for three pavement types was developed and the total pavement maintenance requirement was found to be a function of the pavement's age squared and the number of days when the maximum temperature was below 32^oF. The dependent variables examined in conjunction with each of these identified independent variables were man-hours per lane mile, material costs per lane mile, and total cost per lane mile (labor + equipment + material).

A series of stepwise multiple regression analyses were made on each group and category. The most significant variable to be identified was age. The number of days when the temperature was below 32^oF was the second variable selected in the stepwise regression but its significance level was quite marginal.

An examination of the residuals, from the analyses with age squared being the independent variable, suggested that two of the sections included in the analysis were out of line with the other sections. A study of the characteristics of these two sections, based on their description in the NCHRP Report No. 42, revealed that both had unusually poor subgrades and therefore extraordinary high maintenance requirements. It was determined that this was a suitable basis for eliminating these two sections from the analysis.

The independent variables were restructured to include average annual traffic, age, age squared, age cubed, and the number of days when the maximum temperature was below 32°F. Further, a terrain factor was added to reflect flat through mountainous terrain. Arbitrary values of 1 through 5 were given to flat to mountainous terrain respectively.

In the series of stepwise multiple regressions, age cubed was identified as the most significant variable at the Step 1 level, followed by either age squared or age and then ADT or terrain. The ADT and terrain factors were not considered significant. In the conduct of the analysis a few modifications were made to the terrain factor and a series of ages between age squared and age cubed were also examined. The resulting models and their regression statistics are shown in Table 1 for the bituminous sections and Table 2 for the concrete sections and in Table 3 for all sections combined.

Assumptions were made as to ADT and terrain and for a range of ages, and values were computed for each of the regression models and plotted. These were compared with actual plots of the data from the NCHRP 14-1 study. Typical curve sets are illustrated in Figures 1-3. It was determined that neither the terrain nor the ADT factor

TABLE 1. Stepwise Regression Models Developed for Man-hours, Total Costs and Material Costs for the Combined Activities Patching and Maintenance Resurfacing for Bituminous Sections

Model			r	F	S.E.
Man-hours/Lane Mile	=	$3.3 + .14A^3 - .82A^2$	.931	20	2.1
Student t Value		(3.4) (-2.8)			
Man-hours/Lane Mile	=	$.97 + .28A^3 - 2.38A^2 + 4.57A$	.970	27	1.5
Student t Value		(4.5) (-3.6) (2.5)			
Man-hours/Lane Mile	=	$1.02 + .26A^3 - 2.18A^2 + 4.1A + .007L$			
Student t Value		(4.1) (3.4) (2.3) (1.2)	.978	22	1.5
Total Dollars/Lane Mile	=	$18.1 + .92A^3 - 5.38A^2$	.928	19	13.6
Student t Value		(3.5) (-2.8)			
Total Dollars/Lane Mile	=	$1.9 + 1.88A^3 - 16.3A^2 + 32A$	.976	33	8.7
Student t Value		(5.3) (-4.4) (3.1)			
Total Dollars/Lane Mile	=	$2.2 + 1.7A^3 - 14.7A^2 + 28.4A + .056L$	.988	40	7.0
Student t Value		(5.7) (-4.7) (3.3) (1.9)			
Material/Lane Mile	=	$7.5 + .44A^3 - 2.6A^2$	.908	14	7.3
Student t Value		(3.1) (-2.5)			
Material/Lane Mile	=	$-.6 + .92A^3 - 8.01A^2 + 15.81A$	.960	20	5.3
Student t Value		(4.2) (-3.5) (2.5)			
Material/Lane Mile	=	$-.4 + .801A^3 - 6.97A^2 + 13.5A + .03L$	.983	29	3.9
Student t Value		(4.8) (-4.0) (2.8) (2.3)			

r = Multiple Correlation Coefficient
F = Fisher F for analysis of variance
SE = Standard error of the estimate
A = Age of pavement
L = Accumulated 18-kip Axle Loadings

Source Data: Expenditures reported on 26 sections of Interstate highway in NCHRP Study 14-1 for Patching

TABLE 2. Stepwise Regression Models Developed for Man-hours, Total Costs and Material Costs for the Combined Activities Patching and Maintenance Resurfacing for Concrete Sections

Model			r	F	S.E.
Man-hours/Lane Mile	=	$-4.0 + .055A^3$	.946	136	5.4
Student t Value		(11.7)			
Man-hours/Lane Mile	=	$-20.6 + .054A^3 + 13.54V$	.952	73	5.2
Student t Value		(11.7) (1.4)			
Man-hours/Lane Mile	=	$-22.7 + .055A^3 + 13.9V + .0047T$	.957	51	5.1
Student t Value		(11.9) (1.5) (1.3)			
Total Dollars/Lane Mile	=	$55.8 + .79A^3 - 5.6A^2$	.983	214	17
Student t Value		(5.2) (-3.2)			
Total Dollars/Lane Mile	=	$-22.4 + .78A^3 - 5.4A^2 + 63V$	.988	184	15
Student t Value		(5.8) (-3.6) (2.3)			
Total Dollars/Lane Mile	=	$-31.0 + .77A^3 - 5.4A^2 + 64V + .015T$	.989	149	14
Student t Value		(5.9) (-3.6) (2.4) (1.4)			
Material/Lane Mile	=	$14.6 + .20A^3 - 1.46A^2$	.969	116	5.8
Student t Value		(3.9) (-2.4)			
Material/Lane Mile	=	$-12.6 + .20A^3 - 1.44A^2 + 21.8V$	.978	103	5.0
Student t Value		(4.4) (-2.7) (2.4)			

r = Multiple Correlation Coefficient
F = Fisher F for analysis of variance
SE = Standard error of the estimate
A = Age of pavement
T = AADT (100's)
V = Terrain Factor (Flat = 1.1, Mountain = 1.5)
E = Number of Days when maximum temperature is below $32^{o}F$

Source Data: Expenditures reported on 26 sections of Interstate highways in NCHRP Study 14-1 for Patching

TABLE 3. Stepwise Regression Models Developed for Man-hours, Total Costs and Material Costs for the Combined Activities Patching and Maintenance Resurfacing for All Pavement Sections

Model		Equation	r	F	S.E.
Man-hours/Lane Mile	=	$8.5 + .074A^3 - 3A$	.948	101	4.6
Student t Value		(7.5) (-2.2)			
Man-hours/Lane Mile	=	$-6.6 + .074A^3 - 3.2A + 13V$	.954	74	4.5
Student t Value		(7.8) (-2.5) (1.7)			
Man-hours/Lane Mile	=	$-5.7 + .077A^3 - 3.6A + 12.7V + .005T$	.960	62	4.3
Student t Value		(8.3) (-2.9) (1.8) (1.7)			
Total Dollars/Lane Mile	=	$23.0 + .63A^3 - 3.7A^2$	.978	248	16.5
Student t Value		(8.1) (-4.4)			
Total Dollars/Lane Mile	=	$-48.0 + .639A^3 - 3.84A^2 + 60.5V$	.982	200	15
Student t Value		(9.0) (-5.0) (2.4)			
Total Dollars/Lane Mile	=	$-48.0 + .667A^3 - 4.12A^2 + 58.7V + .02T$	.986	178	14
Student t Value		(10.0) (-5.7) (2.5) (2.2)			
Material/Lane Mile	=	$8.0 + .099A^3 - 3.5A$	.929	72	7.7
Student t Value		(6.0) (-1.6)			
Material/Lane Mile	=	$-15.6 + .099A^3 - 3.8A + 20.45V$	.936	52	7.5
Student t Value		(6.3) (-1.7) (1.6)			

r = Multiple Correlation Coefficient
F = Fisher F for analysis of variance
SE= Standard error of the estimate
A = Age of pavement
T = AADT (100's)
V = Terrain Factor (Flat = 1.1, Mountain = 1.5)
E = Number of Days when maximum temperature is below $32^{o}F$

Source Data: Expenditures reported on 26 sections of Interstate highway in NCHRP Study 14-1 for Patching

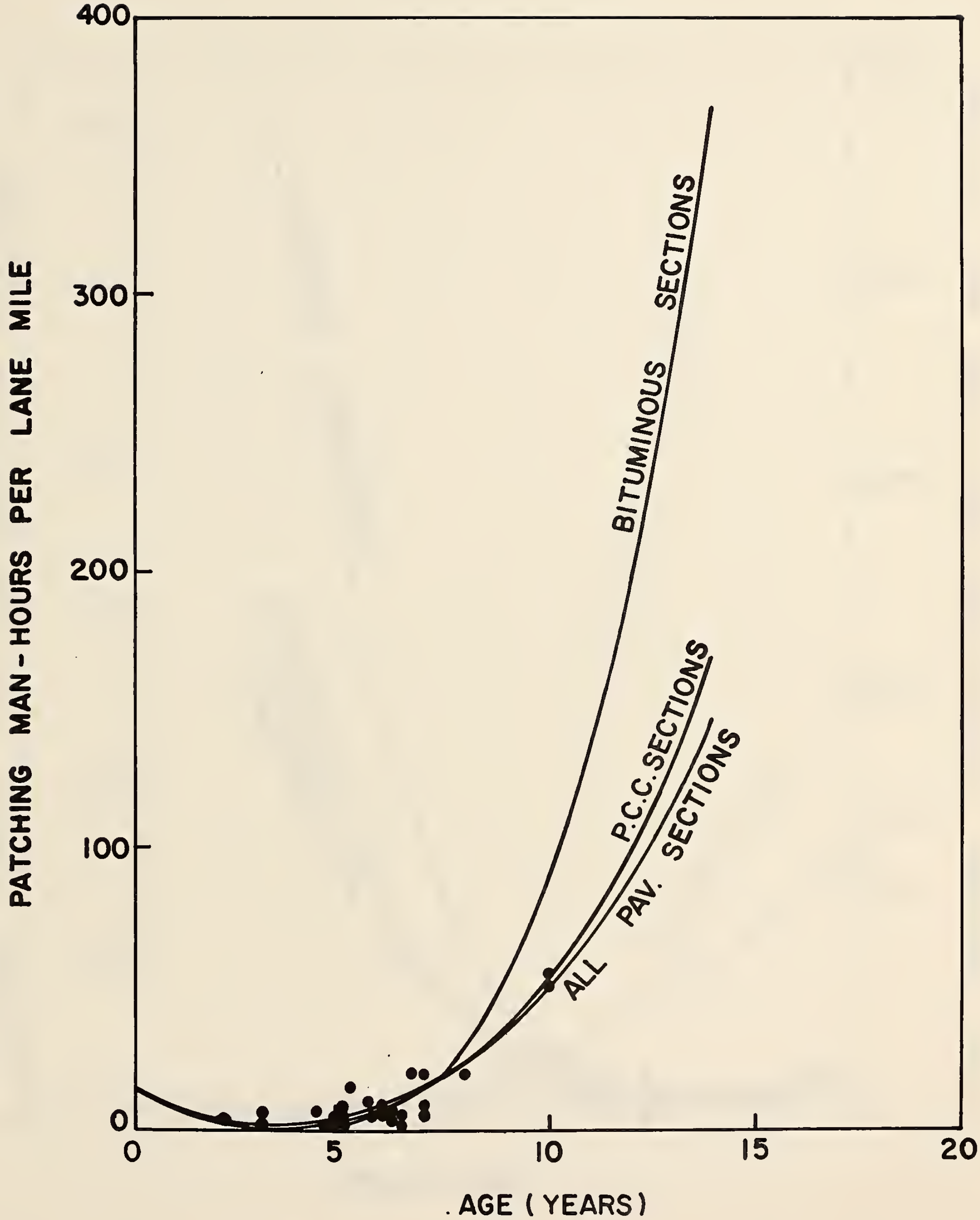


Figure 1. Regression curves for man-hours spent on patching on test sections included in 14-1 study[26]

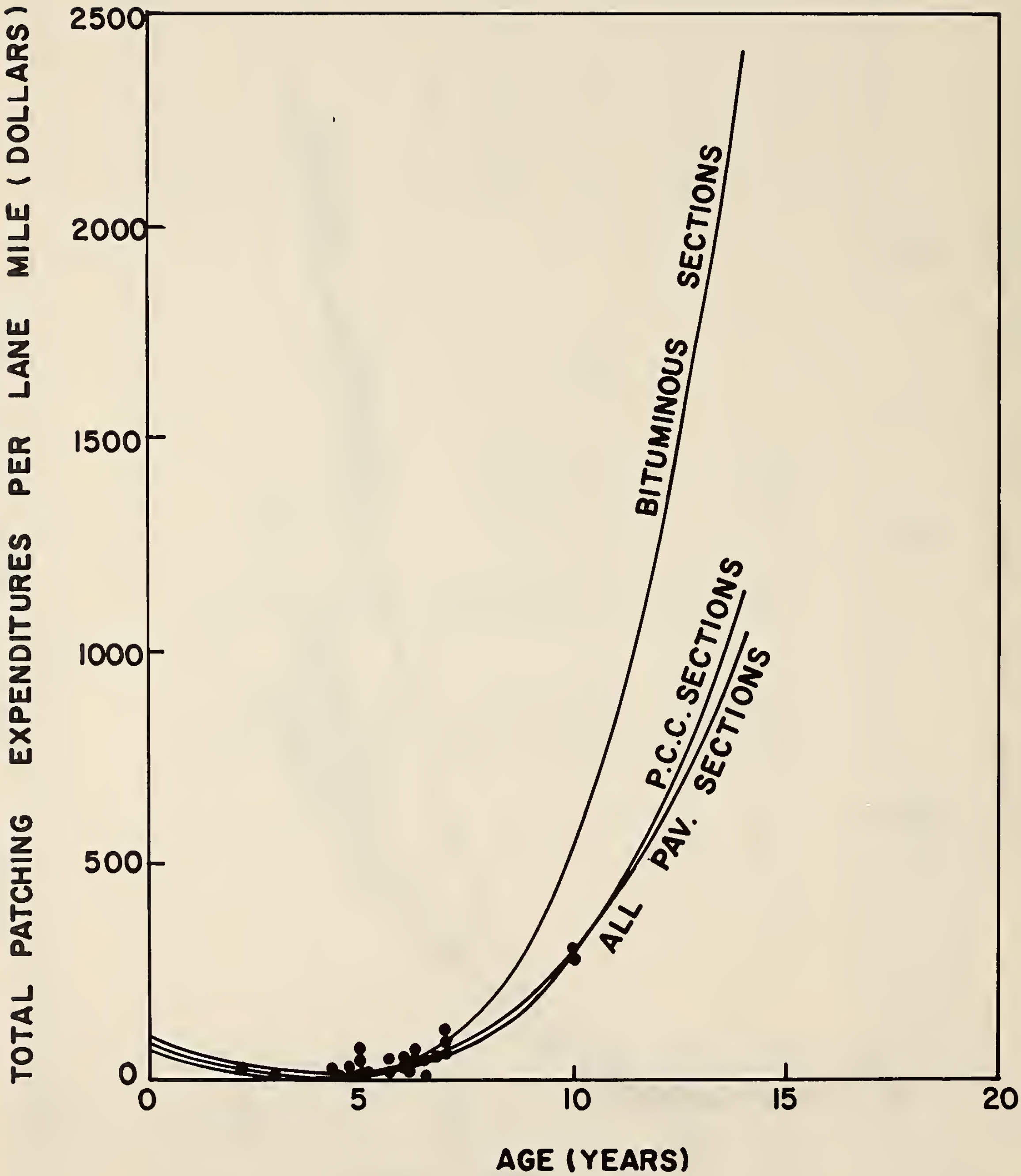


Figure 2. Regression curves for total patching expenditures on test section included in 14-1 study (26)

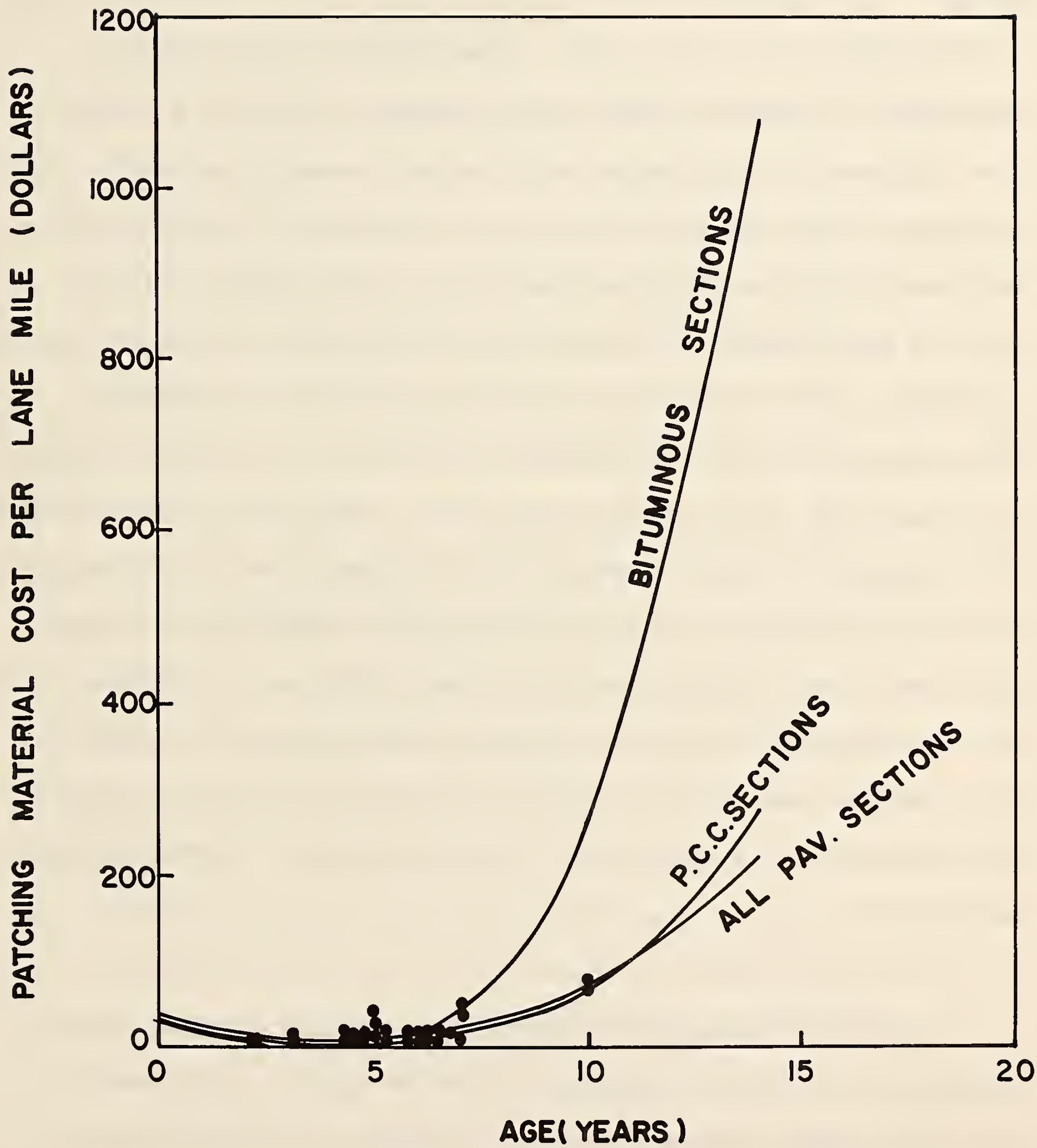


Figure 3. Regression curves for material patching expenditures on test section included in 14-1 study.[26]

contributed significantly to explaining the maintenance patching requirement and therefore these two variables were dropped, leaving just the age.

The shape of the curve, which suggests fairly high maintenance expenditures in the early years, was not deemed realistic. As may be noted in Figures 1-3, the actual data covered a span between the three-year old and ten-year old pavement. Therefore, the portion of the curve prior to age three was based on no data. Other than construction deficiencies, which realistically should not be considered maintenance, there should be no patching expenditures required for a new pavement. Therefore, an assumption that the level of expenditures is zero when age is zero seemed reasonable. Further, the extrapolation of the regression curves beyond ten years produces expenditures that are enormous and there was no data to validate the indefinitely increasing accelerated rate of maintenance expenditures with time. Therefore, it was determined that a reasonable shape for the maintenance patching curve could be represented by a logit function which fit the curve as it exists between ages three and ten. The logit function assumes the following form:

$$y = e^{f(x)}/(1 + e^{f(x)})$$

For each curve group and category, the predicted dependent value (MH, Costs) was scaled to equal 0.5 at the tenth year. This occurs when f(x) becomes zero and provides a mechanism for establishing the desired function of x which was defined as follows:

$$f(x) = (\text{Age} - 10)/D$$

The desired shape of the curve was determined through a trial and error process for D for each group and category. Further, the logit function was multiplied by $1/e^{f(x)}$ and converted to the following form:

$$y = (S/(1 + e^{-(Age-10)/D}))$$

The "S" is a scale factor and becomes two times the original model value for age 10. The resulting equations for bituminous, concrete and combined pavements for both materials dollars and man-hours are shown in Table 4. The plotted curves for the material models for the concrete and bituminous sections are illustrated in Figures 4 and 5.

The model for the maintenance module required for this study must predict the quantity of patching required for a given pavement design. Therefore, the logit models illustrated in Figure 2 for the concrete material and bituminous material were modified to predict quantity as follows. For concrete, it was determined that in 1965 (the year in which the data was developed) the cost per square yard of pavement for concrete was $4.00. Therefore, (136/4) produces 34 square yards of concrete per lane mile as the ultimate workload for an infinite age concrete pavement. For the bituminous pavements, it was determined that in 1965 the cost per ton of bituminous material was $5.00. Assuming a patching thickness of 2 inches and a unit weight of 140 pounds per cubic foot for bituminous materials, then one square yard two inches thick equals 1½ cubic feet of bituminous material or 210 pounds per square yard. This results in approximately one-tenth of a ton per square yard or 50¢ per square yard. The material cost figure of 552 then becomes 1100 square yards. Therefore, the models for concrete

TABLE 4. Logit Models for Pavement Patching

<u>Models</u>

Bituminous Pavements

Material dollars/LM = $552 \times (1/(1 + e^{-(Age-10)/1.16}))$

Man-hours/LM = $176 \times (1/(1 + e^{-(Age-10)/1.20}))$

Concrete Pavements

Material dollars/LM = $136 \times (1/(1 + e^{-(Age-10)/1.25}))$

Man-hours/LM = $102 \times (1/(1 + e^{-(Age-10)1.69}))$

All Pavements

Material dollars/LM = $142 \times (1/(1 + e^{-(Age-10)1.51}))$

Man-hours/LM = $104 \times (1/(1 + e^{-(Age-10)1.51}))$

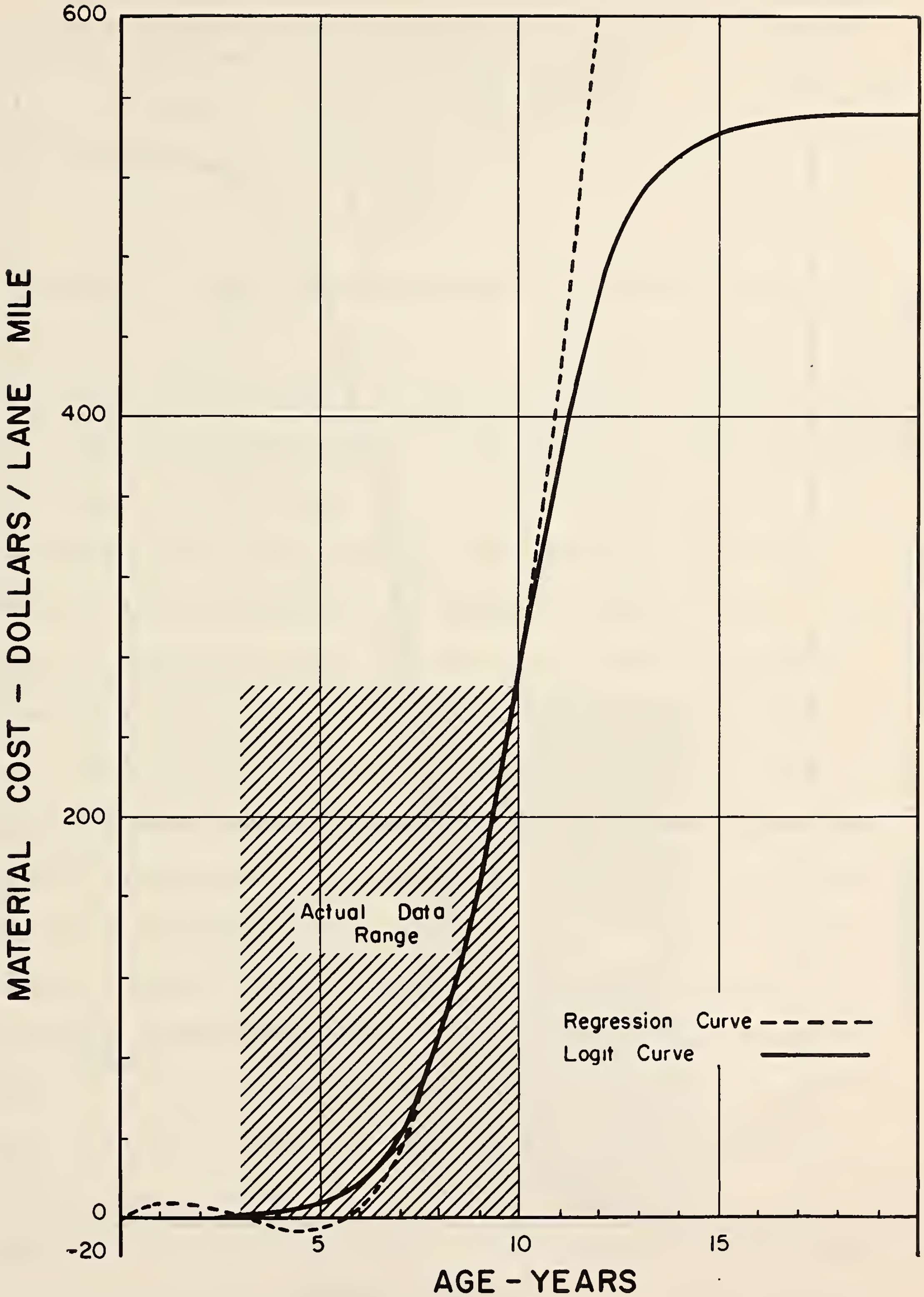


Figure 4. Patching curves for bituminous concrete pavements.

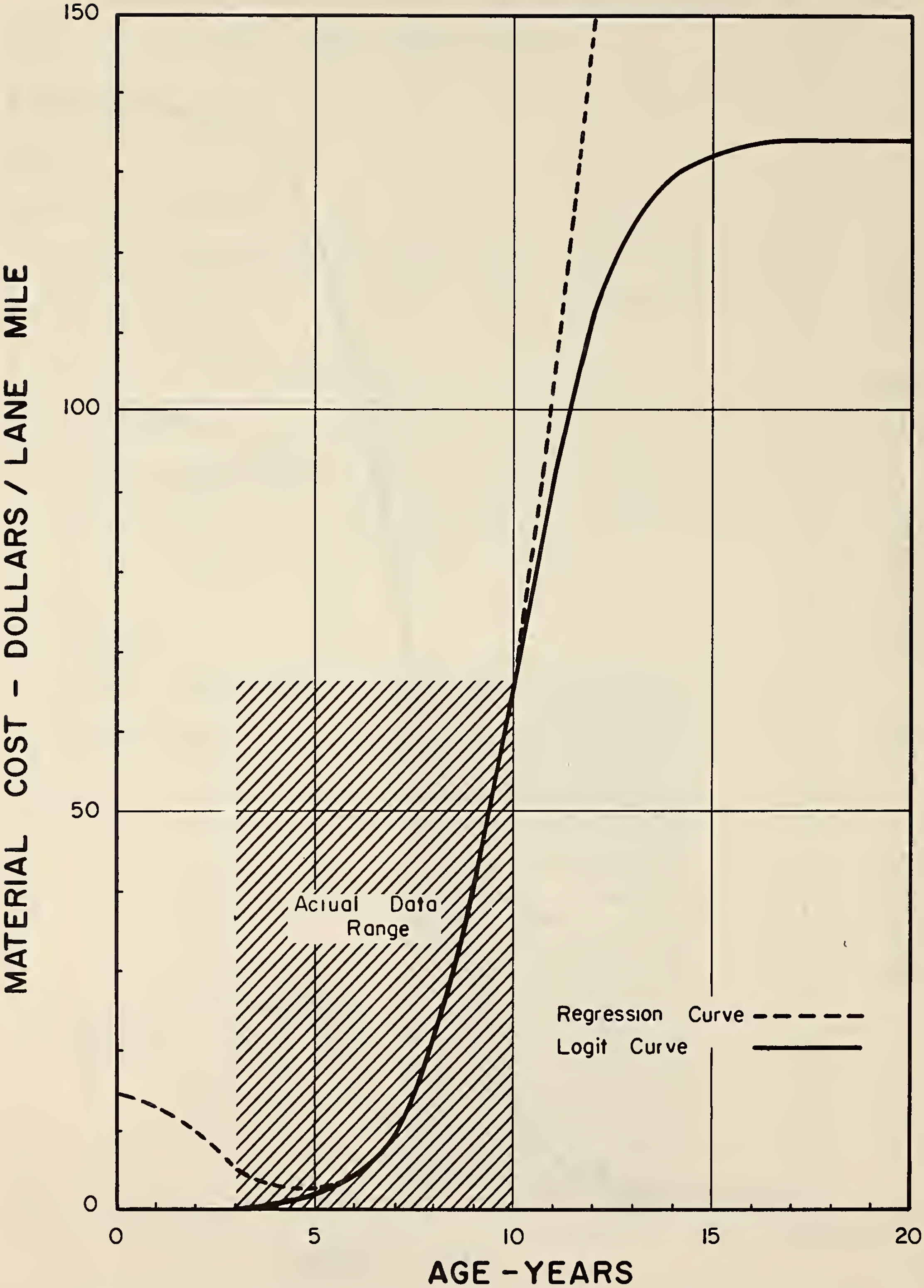


Figure 5. Patching curves for portland cement concrete pavements

and bituminous pavements were as follows:

$$\text{SY concrete} = 34/(1 + e^{-(\text{Age}-10)/1.25})$$

$$\text{SY bituminous} = 1100/(1 + e^{-(\text{Age}-10)/1.16})$$

Blowups

A number of studies have been conducted to identify the cause of concrete blowups.[28-33] Some of these studies cover pavement histories dating back into the Twenties. A number of patterns have been identified but no quantitative mechanism has been developed for predicting blowups. The concensus is that blowups occur at joints in portland cement concrete pavement when high temperatures and the presence of moisture creates excessive expansion of the pavement. These conditions are associated with the summer months and particularly with late afternoons following periods of rain. The study results are vague on other causations. There is mixed opinion relating blowup frequency to both joint spacing and to the presence of expansion joints. There is general agreement that incompressibles are undesirable in the joint. The incompressibles reduce the cross-sectional area in the joint to resist expansion stresses. Further, incompressibles contribute to joint deterioration and spalling which further weakens the joint section thereby enhancing blowups. The consensus is that soft aggregates contribute to blowup frequency principally because soft aggregates are associated with weak portland cement concrete.

In all of the studies reviewed, there was agreement that blowup frequency increases with pavement age. Examples of this are shown in Figure 6 for blowup histories in Michigan and Iowa. The average

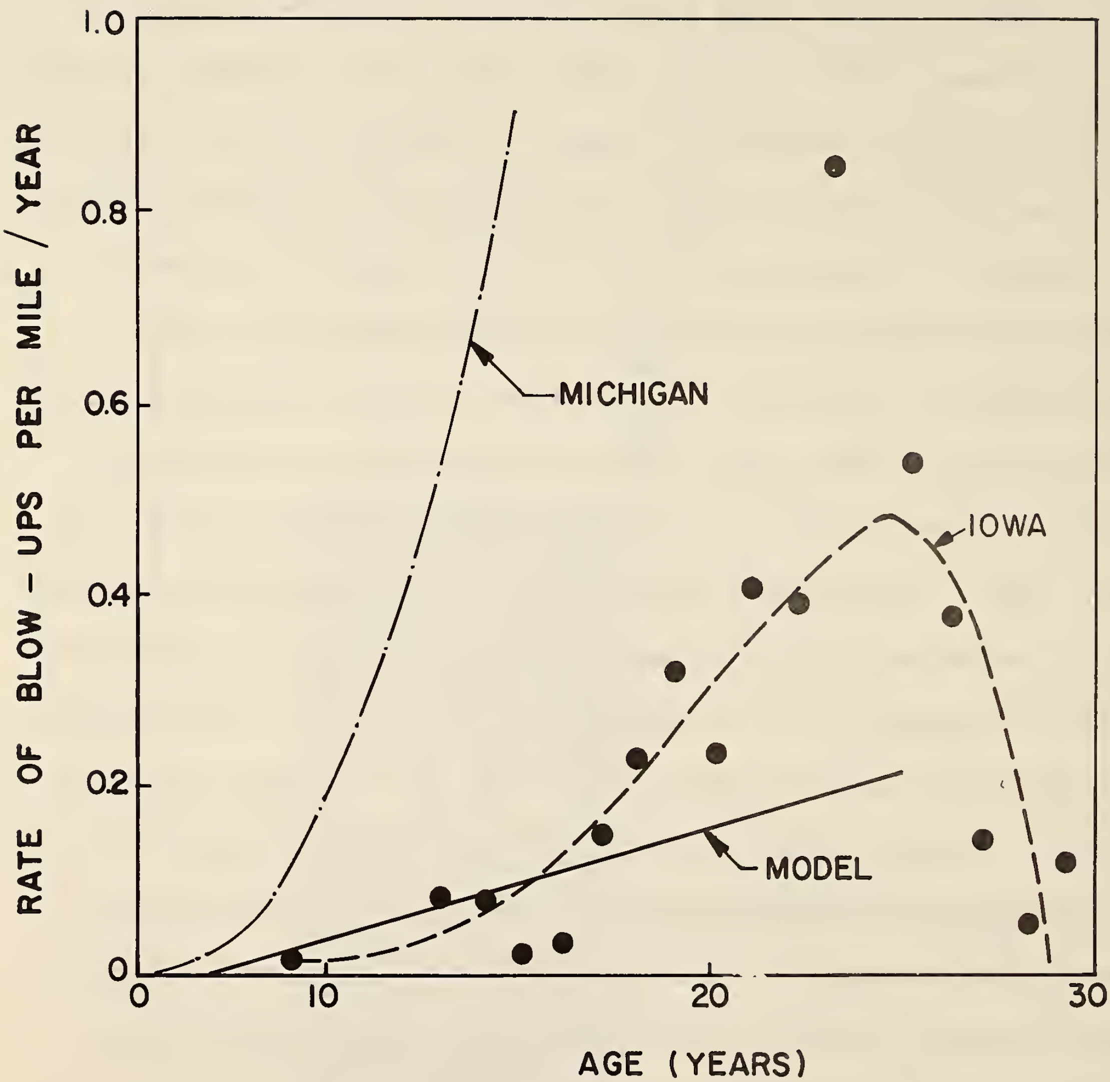


Figure 6. Example of blowup histories in Michigan and Iowa compared with model selected for program

blowup frequency as reported in various state studies was converted to blowups per lane mile and summarized in Table 5. Based on this information and the age relationship, the following blowup model was created to predict blowups for portland cement concrete pavement:

Given

A = Age

B = Blowup per lane mile/year

$B = 0, A \leq 4$

$B = .005(Age - 4), A \leq 25$

$B = 0, A > 25$

The permanent repair of a blowup is assumed to be included in the concrete patching. The additional workload to be associated with the blowup will be that of a temporary patch. The reason for this approach is that the blowup which occurs in the late afternoon has a major impact on traffic and the maintenance crews tend to minimize the extent of the repair at that time before making a quality repair when traffic volumes are not in their peak. Figure 7 illustrates the tendency of blowups to occur in the late afternoon. The blowup is assumed to occur in the lanes that are closed in the analysis.

Mudjacking

Mudjacking or slabjacking is an activity used by many highway agencies to correct the settlement or horizontal alignment of rigid pavements. For one reason or another, voids develop under a rigid pavement. The jacking technique involves forcing a slurry or grout mixture under the

Table 5 . Blowups as reported in various studies (28-33)

Location	Average Blowups per Lane Mile Per Year	Reference
Maryland	.05	28
Ohio Turnpike	.01	28
Illinois	.03	28
Chicago Expressway	.10	28
Iowa	.10	28
Wisconsin	.03	28
Michigan	.05	29
Illinois	.03	30
Arkansas	.11	31
Connecticut Turnpike	.12	32
Indiana	.02	33

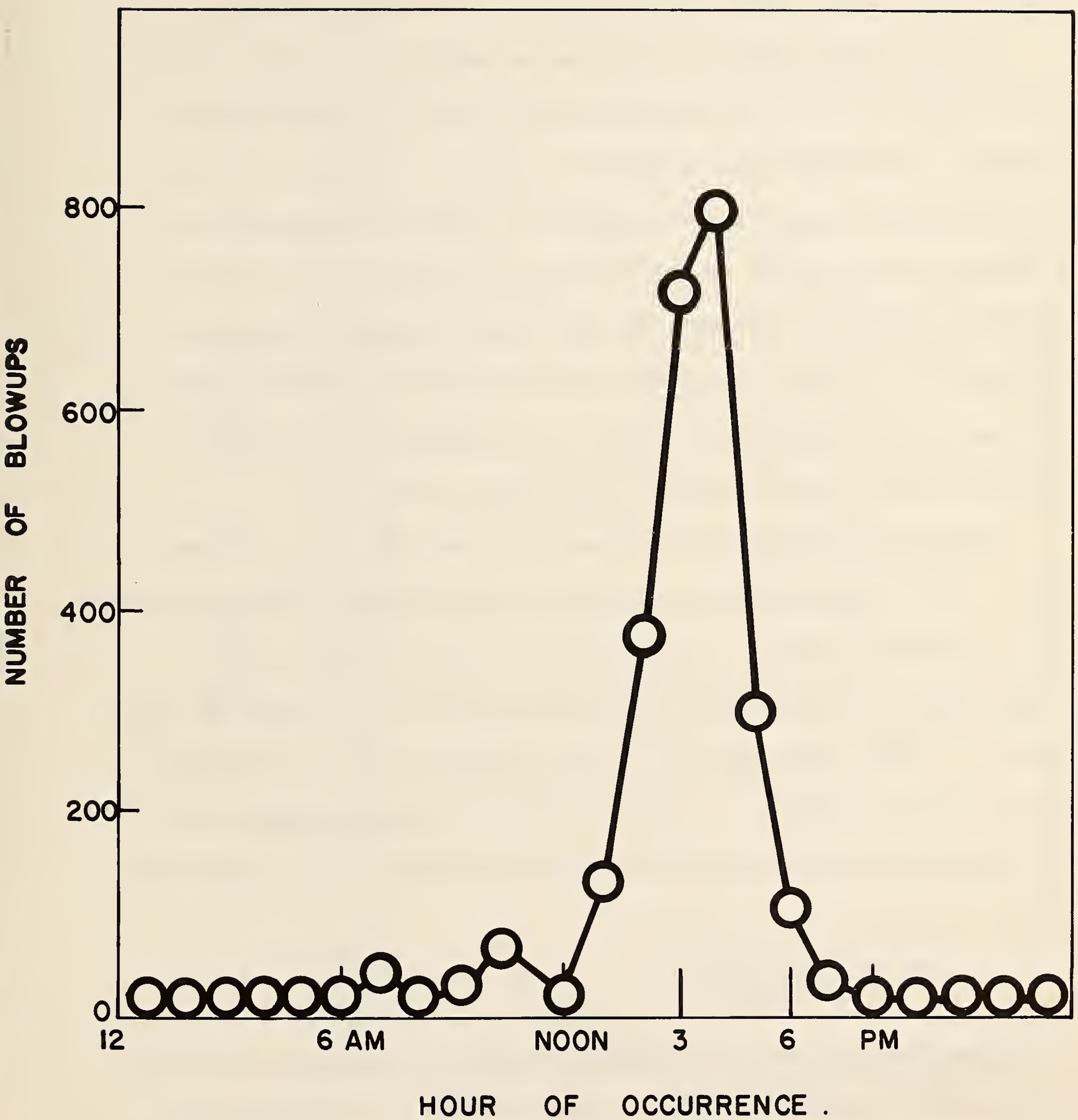


Figure 7. Example of documented hours of blowup occurrence based on Illinois study (30)

slab to fill voids. The hydrostatic pressure developed during the process also can be used to lift the slab to its proper position.

There is wide variation in the use of mudjacking by highway agencies so that it is an activity which may or may not be applicable in the model. Even when this technique is used by an agency, its use is not necessarily common to all pavements. Holbrook reported that in Michigan when mudjacking is practiced, only 22 percent of the rigid pavement construction projects had any mudjacking after 15 years of service.[29] Of these, 11 percent had less than one percent of the pavement surface mudjacked. Figure 8 is a graphic presentation of mudjacking taken from the Oehler and Holbrook report.[29]

Mudjacking when needed occurs early in the life of a rigid pavement. This is documented by the mudjacking expenditure history experienced by the Ohio Turnpike. In Table 6, the total expenditures for mudjacking on the 241 miles, 4-lane divided tollroad are shown by year. Based on a labor wage index, the total expenditures were converted to 1967 dollars and plotted. A study of the plot suggests a gamma curve with mean expenditures occurring in the seventh year. The gamma distribution for any k = 1, 2, 3, ...

$$f x_k(x) = \frac{\lambda(\lambda x)^{k-1} e^{-\lambda x}}{(k-1)!} \qquad x \geq 0$$

X is gamma distributed with parameters k and λ. The mean value (m_x) of the function is defined as k/x and the variance (σ_x^2) is defined by k/λ^2. By assuming a mean of 7 years and a standard deviation of 4 years, k and x can be computed by substitution where:

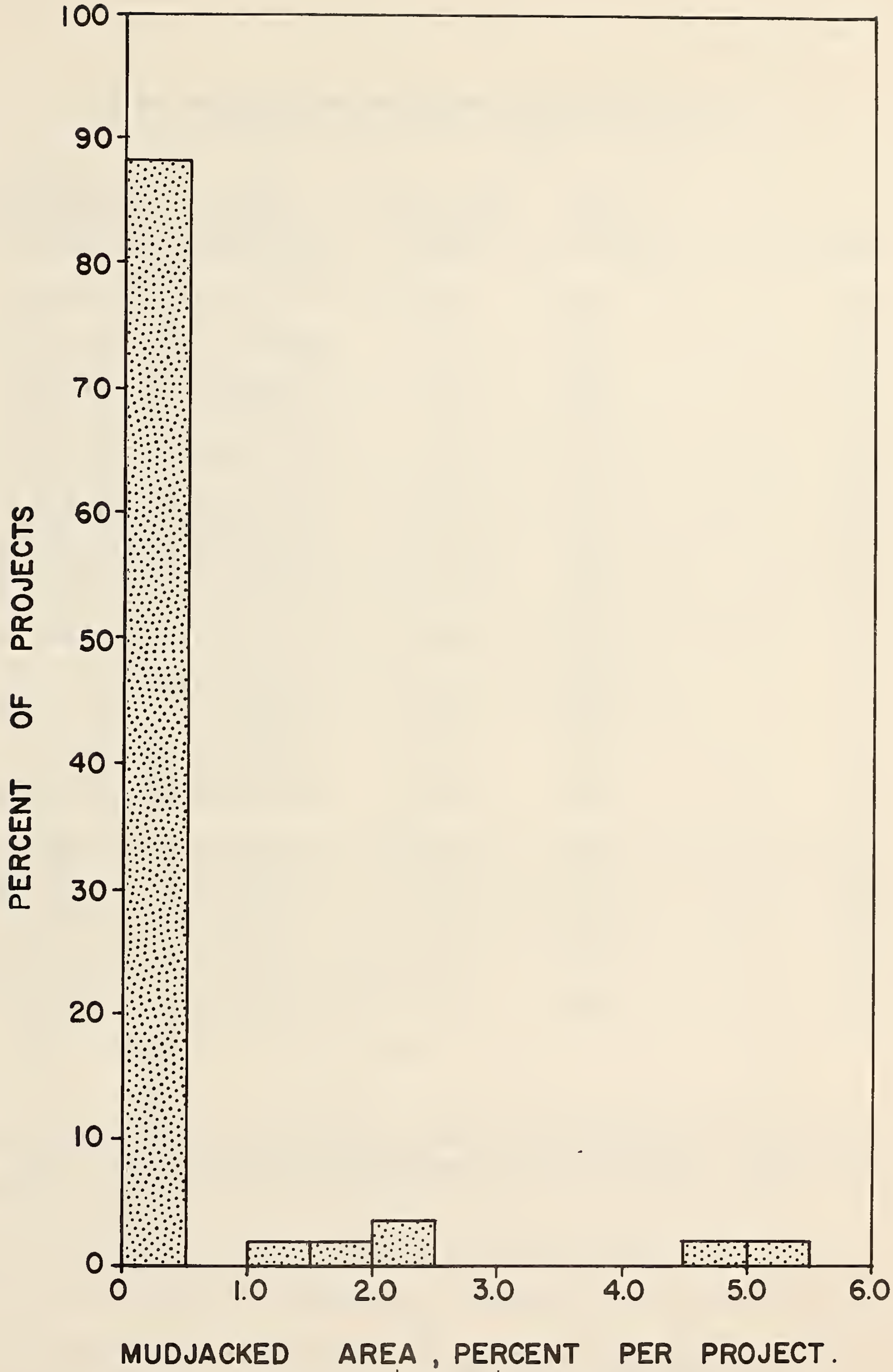


Figure 8. History of mudjacking as recorded in a Michigan Study by Oehler and Holbrook (29)

Table 6. Annual mudjacking expenditures on the Ohio Turnpike adjusted to 1967 dollars.*

YEAR	LABOR RATE	LABOR INDEX (1967)	REPORTED EXPENDITURE	ADJUSTED EXPENDITURE (1967)
1956	1.64	1.86	13,173.91	24,503.47
1957	1.78	1.71	15,579.73	26,641.34
1958	1.85	1.65	35,890.68	59,219.62
1959	2.02	1.51	46,617.48	70,392.39
1960	2.13	1.43	46,617.89	66,663.58
1961	2.31	1.32	26,085.89	34,433.37
1962	2.45	1.24	46,282.92	57,390.82
1963	2.54	1.20	41,293.45	49,552.14
1964	2.60	1.17	39,146.91	45,801.88
1965	2.65	1.15	54,515.89	62,693.27
1966	2.88	1.06	50,862.79	53,914.56
1967	3.05	1.00	33,167.58	33,167.58
1968	3.45	0.88	28,940.39	25,467.54
1969	3.66	0.83	15,766.59	12,086.27
1970	3.87	0.79	11,101.03	8,769.81
1971	4.12	0.74	5,607.97	4,149.90
1972	4.23	0.72	2,424.17	1,745.40
1973	4.58	0.67	5,575.30	3,735.45

*Total annual expenditures are for labor and material. Material costs were minor. Therefore, the adjustment was based on labor alone.

$$m_x = 7 = k/\lambda$$

$$\lambda_x^2 = 16 = k/\lambda^2$$

$$k = 7\lambda$$

$$\lambda_x^2 = 7\lambda/\lambda^2 = 7/\lambda = 16$$

$$\lambda = 7/16 = .4375$$

$$k = 7 \times .4375 = 3.06$$

We wish to have an integer number for k so it was made 3. Further, we wanted to accelerate mudjacking to create a function which would predict 100% mudjacking within a 20-year design period. Therefore, a value of .5 was assigned to λ. This produced the following mudjacking model:

Y_x = Annual percent of design life mudjacking

x = Age in years

$$Y_x = .25(.5x)^2 e^{-.5x}$$

This function is plotted in Figure 9 where it has been factored by 518.52 so it can be compared with the corresponding Ohio Turnpike values. The function sums to .9975 for 20 years.

$$\sum_{x=1}^{x=20} .25(.5x)^2 e^{-.5x} = .9975$$

Based on available information, it was assumed that one percent of the pavement area will be mudjacked over the life of the pavement, if mudjacking is applicable. Therefore, 52.8 feet of each lane mile of pavement will be subject to mudjacking. The mudjacking locations will be based on slab length. Therefore, for 30-foot joint spacing, there will be (52.8/30) = 1.76 mudjack locations per lane mile over the life

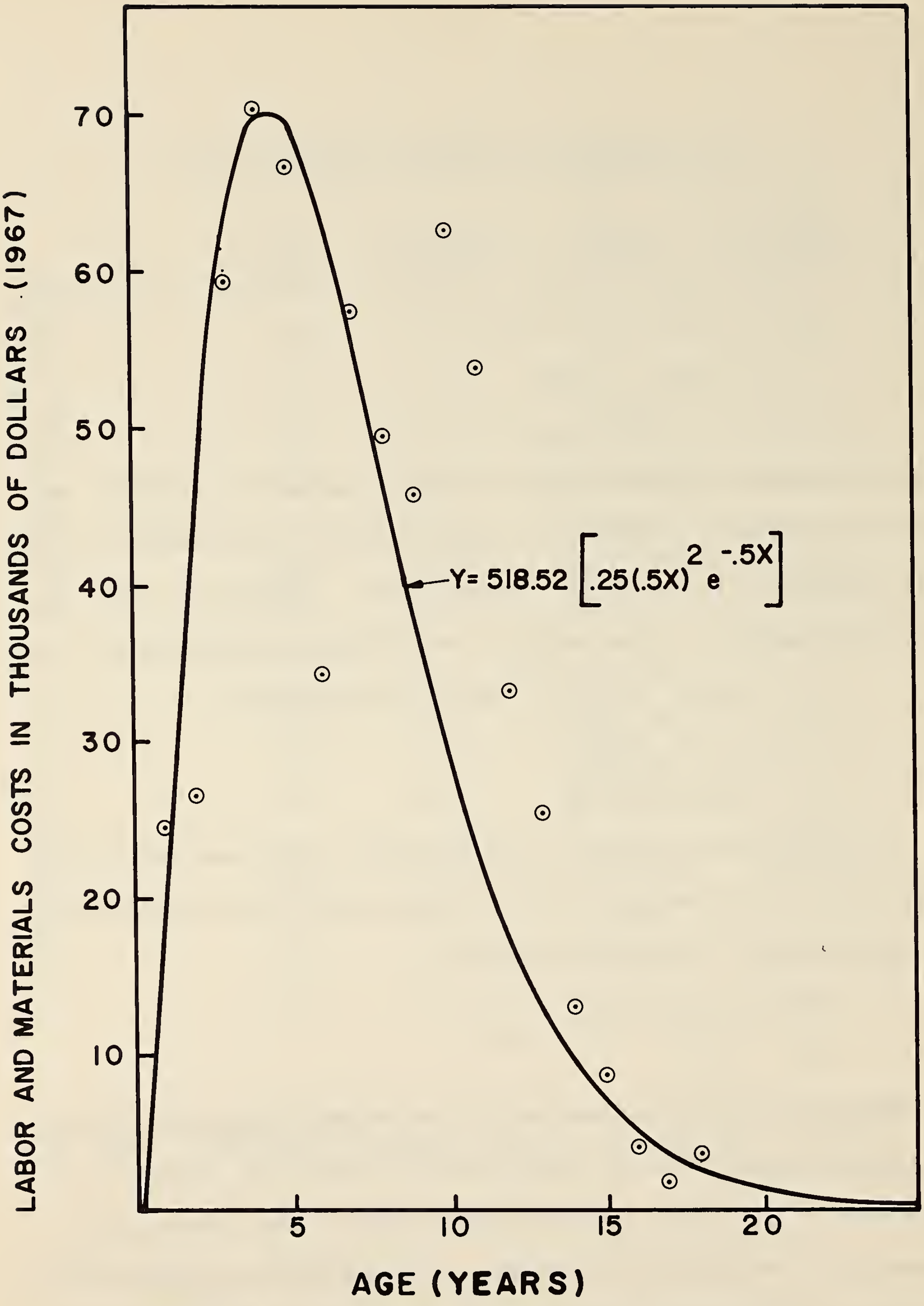


Figure 9. Curve fit to mudjacking expenditures as reported by the Ohio Turnpike after conversion to 1967 dollars

of a rigid pavement. This is the design life mudjacking. The gamma model is used annually to determine the percentage of the design life mudjacking which occurs each year.

Joint Sealing

Concrete contraction joint sealing practices vary widely. Some agencies seal concrete joints annually using bituminous sealants. Other agencies reduce the frequency through the use of more expensive materials including rubberized asphalts and neoprene. The objective in contraction joint sealing is to prevent surface moisture from flowing into the base and subbase where it can lead to pumping, frost heaving and reduced pavement support.

The contraction joint sealing activity workload will be based almost entirely on policy as it relates to sealant material and sealing frequency. The material costs will be reflected in the activity standard. Therefore, the contraction joint sealing workload can be specified entirely through the maintenance level which is defined in Appendix D. The workload will be in linear feet of joint sealing and is computed as follows:

W = Annual Workload per lane mile in linear feet

L = Lane width in feet

ML = Maintenance level

S = Joint spacing in feet

$$W = ((5280 \times L)/S) \times ML$$

Crack Sealing

The literature and workload data from recent maintenance management studies revealed that the range of crack sealing varied from 1 to 10 gallons and from 50 to 100 pounds of filler material per lane mile. Some agencies do not seal bituminous cracks contending that it does not do any good. Nevertheless, a workload model was developed for bituminous crack sealing. It is based on the patching model and an average reported quantity.

First, the reported gallons and pounds of sealant material were converted to cubic inches. This was accomplished by assuming the sealant to have a specific gravity of one. Conversion of the reported workload range to cubic inches is shown in Table 7 producing a range from 231 to 2770 cubic inches per lane mile.

Table 7. Joint sealing material conversion

Material Range		Conversion	
Pounds	Gallons	Factor	Cubic Inches
50		1728/62.4	1385
100		1728/62.4	2769
	1	231	231
	10	231	2310

The workload is expressed in linear feet of cracks to be filled so the assumption was made that 10 cubic inches of sealant was needed per linear foot of crack. The range of linear feet varies from 23 to 277 per lane mile from the following computation:

231/10 = 23.1

2770/10 = 277

The average linear feet of crack sealing would be as follows:

$$\text{Av. crack sealing per lane mile} = \frac{(23 + 277)}{2} = 150$$

Assuming that the bituminous pavement is resurfaced after 12 years means that the average crack sealing level occurs in the eighth year. To modify the bituminous patch model for crack sealing, the coefficient must be changed. This is easily accomplished by having the model predict 150 linear feet in the eighth year. Substitution of an age of eight into the bituminous model results in the prediction of 165 square yards of bituminous patching. A direct ratio as follows converts the coefficient for crack sealing:

$$\text{SY Bituminous Patch} = 1100/(1 + e^{-(\text{Age}-10)/1.16})$$

$$= 1100/(1 + e^{-(8 - 10)/1.16}) = 165$$

$$(150/165) \times 1100 = 999.9$$

$$\text{LnFt Crack Sealing} = 1000/(1 + e^{-(\text{Age}-10)/1.16})$$

Bituminous Base and Surface Repair

Information available from the NCHRP 14-1 study and other recent management studies[34-37] conducted by the consultant and others was studied and a range of from .1 to 3 tons of repair per lane mile was established as the workload range. The assumption was made that the base and surface repair workload would follow the shape of the patching model for bituminous pavements. It then became necessary to relate the relative level to the patching level.

An average workload of 1.55 tons of repair per lane mile was converted to .775 cubic yards by assuming 2 tons of base and surface repair equaled one cubic yard.

The average patching workload for bituminous pavement will occur in about the eighth year assuming that the resurfacing occurs in the 11th or 12th year, so from the patching model the workload in the eighth year would be about 165 SY per mile as shown under joint sealing.

The coefficient for a base and surface repair model can be established by proportioning the .775 cubic yards to the 165 SYs of patching in the average year.

The patching model factor is 1100, so the required base and surface repair coefficient becomes (1100 x .775/165) = 5.16. This was rounded to 5. Therefore, the base and surface model become

$$\text{Cubic Yards} = 5/(1 + e^{-(\text{Age}-10)/1.16})$$

Composite or Overlayed Concrete Pavement

The models used for the composite pavement were the same as those used in the concrete except that full and partial depth concrete patches were replaced by the bituminous patch model and the joint sealing was replaced by the crack sealing model.

Workload Program Modifications

The workload models outlined for inclusion in the program EAROMAR are actually program default workloads. The program is structured to permit the user to specify his own workload rates. This can be done in two ways. First, the user can directly factor the values generated by the default models. In this way, the annual workload rate can be increased or decreased to accommodate local conditions. This approach retains the influence that the variable age has in the default models. The second option available to the user is the specification of a fixed annual workload rate. This option causes the default model to be by-passed completely. This option also can be used to specify workloads for activities undefined in the program.

Axle Loading Modification to Maintenance Workload Models

It was recognized that maintenance workload models which completely ignore the detrimental effect of heavy axle loadings in deteriorating the pavement are not completely realistic. However, for those sections in the NCHRP Study 14-1 on which the models were based, the traffic volumes, particularly commercial, were not extremely severe. Consequently, axle loadings did not become a significant variable in the workload models.

Starting in 1967 the consultant developed a series of pavement serviceability measures on the Illinois Toll Road[38-40] The traffic volume on this facility is comparable to that which was experienced on the sections monitored in the 14-1 study. For the Illinois Toll Road, accumulated 18-kip axle loadings were computed for each of some 46 different segments of the Toll Road system. The measured serviceability was compared with the PSI predicted by the AASHO road test equations and revealed that only a portion of the loss in service life could be attributed to the history of axles to which the pavement had been subjected. This portion ranged from 25 to 50 percent, averaging about 40%.

The service life measurements, in terms of PSI, were available for the Toll Road for its initial year and established by the consultant in 1967, 1969 and 1971. Drawing a smooth service life curve through these four points revealed that almost every section on the Toll Road will reach a terminal 1.5 Present Serviceability Index level at an age between 19 and 21 years. Figure 10 illustrates four typical curves from the Illinois Toll Road Study. The variation in the initial serviceability index on the pavement ranged from 3.6 to 4.3. Based on AASHO,

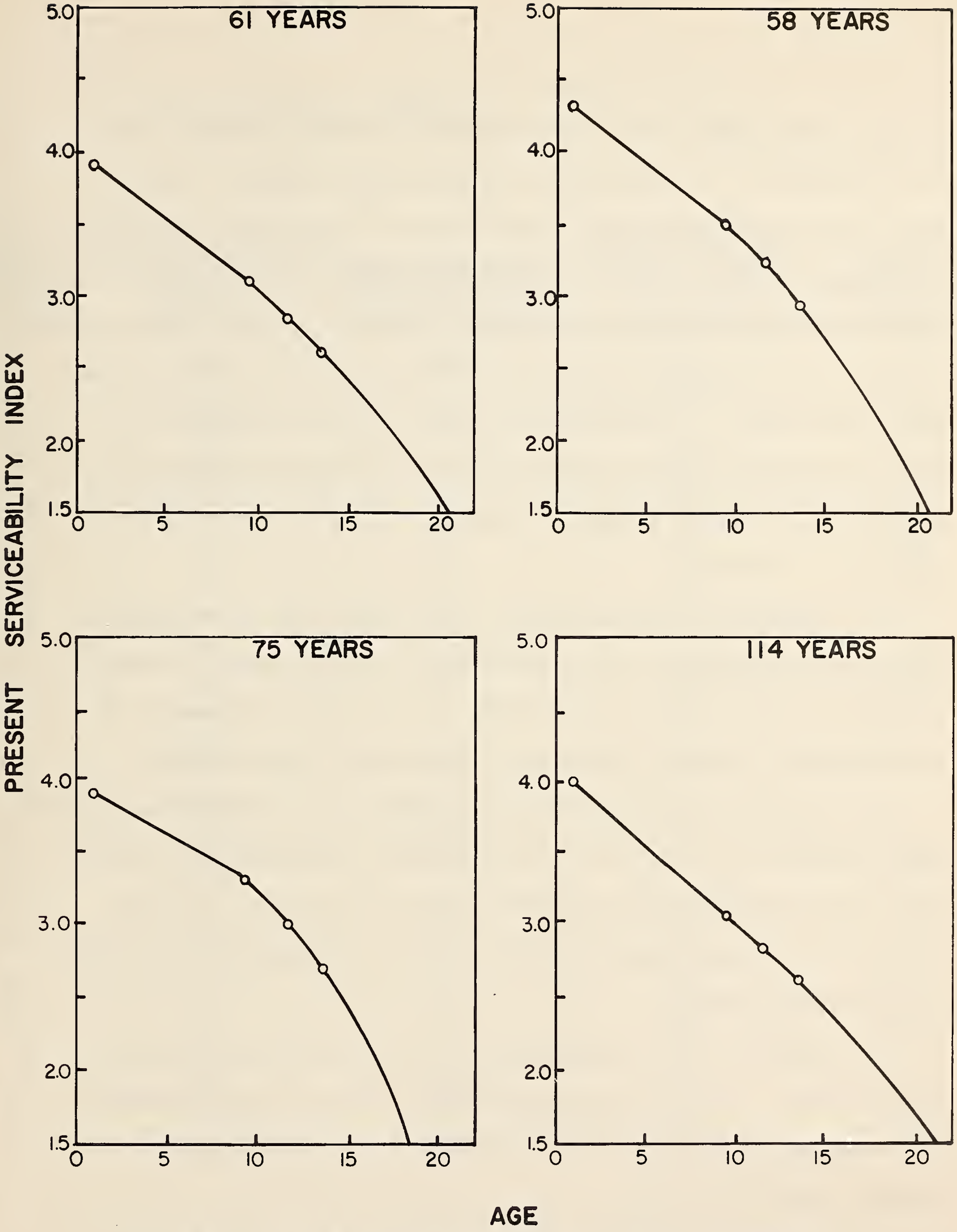


Figure 10. Typical performance curves for sections of the Illinois Toll Road where the failure age based on AASHO computation would have been 61, 58, 75 and 114 years.

the axle loading history would have predicted life spans ranging from 41 to 114 years.[41] These figures are tabulated in Table 8. Therefore, it was concluded that the deterioration of the Illinois Toll Road riding surface proved to be almost completely independent of axle loadings and the initial Present Serviceability Index. In another study by Utah, it also was shown that loss of PSI was more related to age than 18-kip axle loads.[45] These results suggest that the pavement model developed from the NCHRP 14-1 data, where the maintenance requirements are strictly a function of age, is an appropriate model for roads with this level of traffic.

In a comparable study conducted in the Chicago area on the expressway system, the measured present serviceability values closely followed the AASHO road test predictions.[42-44] In this case, the measure of serviceability could be almost entirely attributed to axle loadings.

So, although the maintenance workload models are acceptable for normal traffic loading levels, there will be times when a pavement will be subjected to an extremely large accumulation of axle loadings. When this happens, the workload models must be modified to accommodate the pronounced axle loading effects.

For purposes of the program analysis, a definition was needed for normal traffic. The definition established is based on the AASHO road test equations which predict the accumulated 18-kip axle loads to pavement failure (1.5 PSI).

The two failure equations from the AASHO road test study used in the analysis program follow:

Table 8 . Pavement serviceability relationships based on Illinois Toll Roads studies

Base Year 18-Kip Axle Loadings in Millions	Annual Increase in 18-Kip Axle Loadings in Millions	AASHO Based Years to Failure for 10-inch PCC Pavement	Actual Prediction of Failure Based on Service-Life History	Base Year Present Serviceability Index
2.19	.02	75	19	3.90
2.33	.12	45	21	3.60
.88	.22	41	20	3.60
.73	.22	42	20	3.95
.88	.19	44	19	3.85
1.90	.17	41	20	4.00
1.02	.11	55	20	4.00
.95	.04	84	19	4.30
1.24	.14	48	19	4.20
1.02	.16	47	19	4.00
.73	.12	55	19	3.95
.58	.10	61	19	3.95
.22	.03	114	20	
1.09	.19	43	20	4.05
.88	.20	43	19	4.05
.73	.22	42	20	3.80
.44	.13	55	21	3.70
.37	.11	58	20	4.25
.22	.12	65	20	4.05
.37	.09	66	20	4.05
.15	.12	60	20	3.50
.95	.04	84	21	3.85

Concrete Pavement Equation

T = Pavement thickness inches

ρ = Accumulated 18-kip equivalent axle loadings to produce a terminal PSI value of 1.5

$\rho = (10^{5.85}(T+1)^{7.35})/(19^{4.62})$

Bituminous pavement equation

D = Equivalent pavement thickness

D_1 = Surface thickness inches

D_2 = Base thickness inches

D_3 = Subbase thickness inches

$D = .43D_1 + .14D_2 + .11D_3$

ρ = Accumulated 18-kip equivalent axle loadings to produce a terminal PSI value of 1.5

$\rho = (10^{5.93}(D+1)^{9.36}/(19^{4.33})$

An initial step in the program analysis process is the computation of the 18-kip accumulated axle loads required to fail a designed pavement based on the above AASHO equations.

Normal traffic is defined as any accumulated 18-axle loadings that do not exceed the accumulated axles computed by assuming a uniform annual loading rate which will produce the AASHO failure loading in twenty years. For example, the substitution of a 10-inch PCC pavement design into the AASHO equation predicts that the following axle loadings are required to produce pavement failure:

$\rho = 10^{5.85}(10 + 1)^{7.35})/(19^{4.62})$

$\rho = 39.48 \times 10^6$

Therefore, the limiting annual axle loading rate for normal traffic becomes

$$39.48 \times 10^6/20 = 1.97 \times 10^6 \quad \text{18-kip axles/yr.}$$

In the analysis, the program generates 18-kip axle loadings based on traffic input parameters. As long as these loadings do not exceed the normal levels, no workload model modifications are required. As an example, assume that at the end of ten years 18×10^6 - 18-kip axles had been accumulated. The normal level at the end of ten years is as follows:

$$(1.97 \times 10^6) \times (10) = 19.7 \times 10^6$$

Because 18×10^6 is less than 19.7×10^6, we are within the normal range and therefore no model modification is needed. If, however, the analysis had produced 25×10^6 accumulated axle loadings at the end of ten years, a modification would be required. The modification not only applies to the workload models but to the pavement rehabilitation logic.

Under normal traffic loading conditions, the pavement is assumed to deteriorate at a uniform rate over time. This uniform deterioration is expressed in terms of a uniform loss of psi. In the program, a PSI of 4.5 is assigned to any new pavement. Failure has been defined as 1.5 PSI. Therefore, the normal deterioration process results in a .15 PSI loss per year over 20 years.

$$(4.5 - 1.5)/20 = .15$$

This assumption of a linear loss in PSI serves as the basis for the modification to the workload models.

Under normal traffic loading conditions the PSI loss is linear and requires 20 years to reach 1.5 PSI. The age used in the workload models is based on this deterioration process over a twenty-year period. If the deterioration process is accelerated because of an excessive axle loading rate, the pavement will fail prior to the 20th year. However, the maintenance workload at failure should be comparable to the workload at the 20th year under the normal deterioration process. Therefore, a value of twenty should be used for age in the workload model. The "20" is defined as an equivalent age based on the accelerated deterioration process. The total accumulated 18-kip axles required to fail the pavement are equated to the total available PSI loss to failure, or

$$39.48 \times 10^6 \text{ 18-kip loading} = 3.00 \text{ PSI}$$

and annually

$$1.98 \times 10^6 \text{ 18-kip loadings} = .15 \text{ PSI.}$$

Therefore, for purposes of modifying the pavement patching model, the following procedure was established:

A. If the pavement design module provides a PSI value then the program determines an equivalent age based on a linear interpolation of a total loss of PSI over 20 years.

B. If the pavement design module transfer no PSI value but an axle loading value (18-kips accumulated loadings for the pavements present age), the program compares the transferred axles to the normal traffic loadings, which are based on a linear interpretation of accumulated loadings to a terminal value of 1.5 in 20 years. If the actual loading exceeds the normal loading for a given age, then the PSI is set equal to a comparable axle loading year.

C. If the program provides neither a PSI nor an accumulated loading value, then the accumulated loading will be based on the commercial volume and the commercial axle distribution defined for the program. This computed accumulated axle loading value is compared with an AASHO predicted axle loading value based on a linear interpolation over 20 years. Again, if the actual loading (based on volume) exceeds the predicted loading required, then the age is increased to a comparable axle loading year.

The following are examples of the three conditions A, B, and C as handled by the program:

A. Given: PSI = 2.0, Age = 10 years

With an initial PSI of 4.5, the PSI value at age ten would normally be the following:

$$4.5 - (10 \times .15) = 3.0$$

However, the PSI is given, so an equivalent age is determined. This is computed as follows:

$$\text{Age} = 20 \times (4.5 - 2.0)/3 = 16.67 \text{ years}$$

B. Given: 18-kip Accumulated Loading = 23×10^6

Age = 10 years

Concrete thickness = 10 inches

From the concrete equation on Page 46 the accumulated 18-kip loadings to failure (PSI = 1.5) is 39.48×10^6. This would produce 19.74×10^6 in ten years. The actual loading exceeds this value so the equivalent age is determined as follows:

$$\text{Age} = \frac{23 \times 10^6}{39.48 \times 10^6} \times 20 = 11.64 \text{ years}$$

The program uses an age of 11.64 in the maintenance workload models. Further, the psi is based on the equivalent age in a linear interpolation over 20 years.

C. The modification here is the same as in B. The only difference is that program generates an accumulated axle loading for each analysis year.

A schematic of options A, B, and C is illustrated in Figure 11.

The 18-kip equivalent axle loading factor used in the program is based on the vehicle distribution shown in Table 9 where the composite 18-kip axles are shown to be 735 per 1000 commercial vehicles.

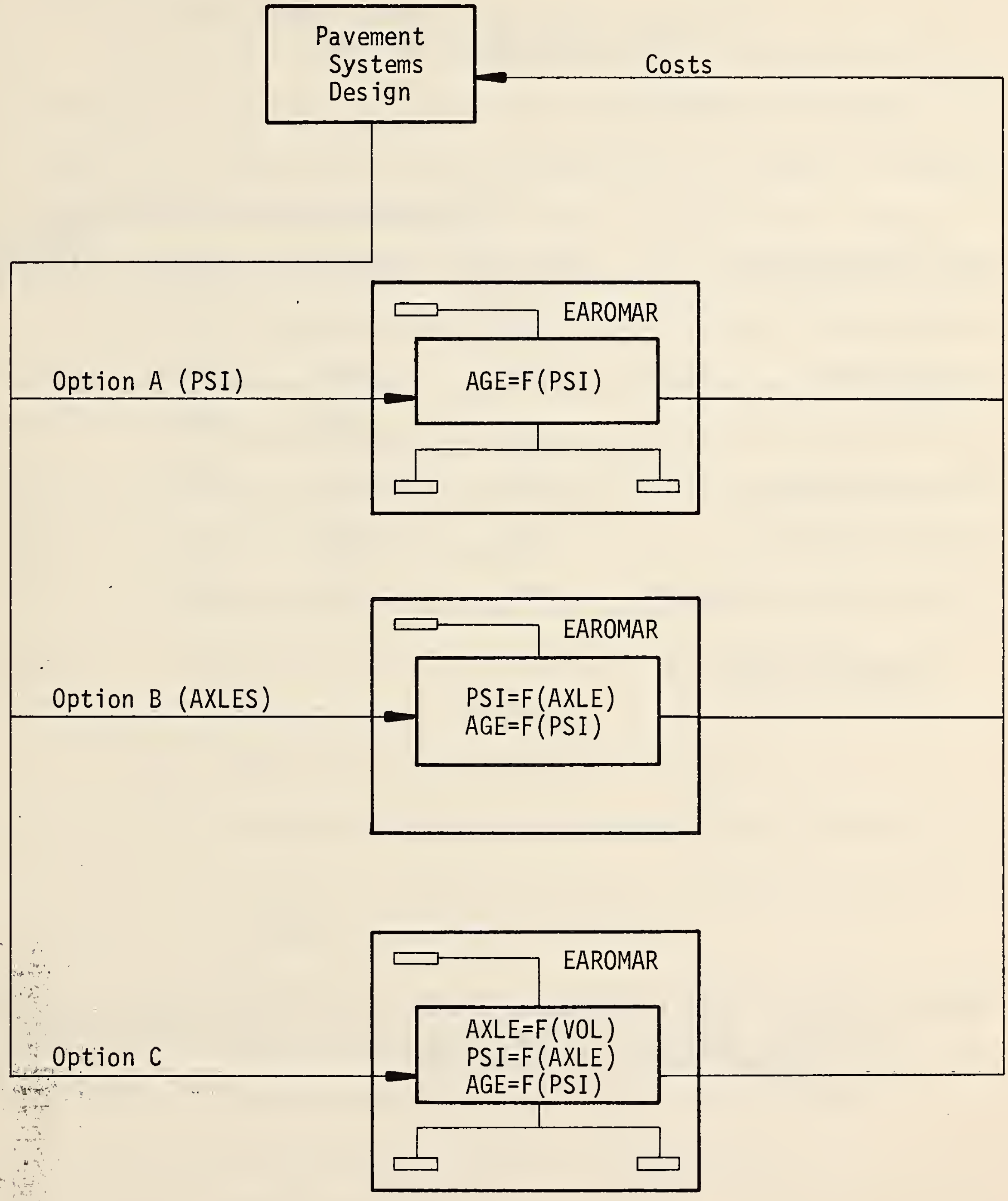


Figure 11. Schematic of PSI axle loading and null transfer options available to pavement systems design program in accessing program EAROMAR, Economic Analysis of Roadway Occupancy for Maintenance and Reconstruction

Table 9. Equivalent 18-kip single axle loads per thousand vehicles.

Vehicle Description	18-K equivalents per 1000 Vehicles Observed	Overloaded	Combined	Commercial Percentage
4 tire	0.4	--	0	--
2 axle 6 tire	134	3360	247	27
3 axle single	422	2160	482	6
3 axle combination	448	6720	667	12
4 axle combination	752	5520	919	26
5 or more axle combination	990	4320	1106	29
Weighted Average			735	100

Source: "Illinois State Toll Highway System...Long Range Pavement Maintenance Program." Bertram D. Tallamy Associates for the Illinois State Toll Highway Commission, March 1968.

Work Requirements

Once the workload is established or accumulated through a given analysis year through the use of the workload models, it becomes necessary to convert this into maintenance costs and motorist impacts. This requires a determination of the hours needed for work crews to perform the predicted annual workload for each work activity.

For a fixed workload, these hours can vary widely, depending on local policy and practices. Some of the influences are as follows:

1. The total available worktime for each crew
2. The policy decisions relating to the periods when the road can be occupied
3. The cure time available for performing the work as the crew must terminate productive activity within the production and cure time
4. Lunch hour policies relating to occupancy
5. The travel allowance for the crew to move from the crew quarters or garage facilities to the work site on the roadway and return
6. The time required for the installation of traffic control.
7. The time spent moving between worksites within a traffic control zone and between traffic control zones
8. The length and character of the work zone
9. The productivity of the work crew
10. The level of maintenance which controls how frequently road will be occupied to perform work

Each of the above factors is part of a simulation process developed to determine the crew hours and the hours of roadway occupancy needed to perform the activity workload which is generated by the workload models.

The program, which was designed to perform the economic analysis, permits each of the above factors to be specified by the program user.

Simulation Process

The expected wide variations relating to constraints on the performance of work dictated a simulation of the work as a reasonable approach to the development of work time requirements. In general, the simulation process involves the following steps anytime an annual workload for an activity has been determined:

1. The maintenance level for the activity is examined and a determination made of the workload to be performed during the simulation process. Three options are possible:
   A. No work will be simulated and the workload will be held over to be added to the workload generated in the next analysis year
   B. All the workload will be included in the simulation
   C. The workload can be divided into a number of equal parts and one part will be simulated
2. The roadway constraints are examined and the first hour of occupancy determined.
3. The magnitude and location of the first worksite is computed.

4. The crew is assigned to the first worksite and based on production data, the time required to complete the work computed.
5. The elapsed time available for roadway occupancy is computed and is based on crew and occupancy constraints.
6. The time required to move to and complete work at the next worksite is added to expended work time, and if within the available elapsed time, the simulation continues to iterate.
7. Following the termination of each occupancy interval, crew hours and occupancy hours by hour are accumulated.
8. The simulation process is performed for each feasible lane closure for each work activity.

Worksite

The wide variation in the way maintenance is handled by different state agencies directed the decision to use a roadway occupancy simulation process to predict the hours of roadway occupancy. One of the variables is the magnitude of the work which will be performed at each worksite. This variable can be random and the result of local policy and practice.

Pavement patching represents the major activity where random variations will occur in worksite size. Therefore, it was decided to establish an array of random size patches in the program. Also, worksite locations will be randomly spaced and this in conjunction with random worksite sizes will produce considerable variations in the required roadway occupancy periods, particularly when subjected to local constraints relating to permitted occupancy hours and work crew schedules.

Three random arrays are established in the program. These are full depth concrete patching, partial depth concrete patching and a roadway location random number. Each array numbers 1000 and this represents the maximum number of iterations permitted in the roadway occupancy simulation for a given activity.

The magnitude and the character of the simulation process can be input to the program for each activity by the user. In this way, the user can structure the work process to resemble local practices.

The character of the simulation process is controlled by the following elements:

1. Size of worksite
2. Number of simulation iterations
3. Spacing of worksite locations

Size of Worksite

Use is made of the two random size patch arrays when the worksite varies. Further, the size can be modified through the use of a factor or an add on permitting wide flexibility in establishing the amount of work which will be done at each worksite.

A third option available to the user in the establishment of work at a worksite is the number of lanes closed to traffic. As an example, in joint sealing, the linear feet at each worksite would double if two lanes instead of one lane were closed to traffic.

The computation of the magnitude of the worksite in the program is structured in the following manner:

W_i = Worksite type where:
- W_1 = Full size patch in square yards
- W_2 = Partial depth patch in square feet
- W_3 = Lanes closed

F = Worksite type multiplier

A = Worksite type add-on

S = Magnitude of the work at each worksite

$$S = W_i \times F + A$$

Simulation Interations

The user can control the magnitude of the simulation process used to establish the required hours of roadway occupancy. This is necessary because there may be no need to simulate an occupancy process when there is no variation in the work process. As an example, a concrete blowup requires that crews occupy the road at one worksite, perform work and leave the roadway. If the workload is specified as sites, then repeated iterations would be redundant. In this case a single iteration of the simulation would produce the same results and therefore is all that should be specified to the program.

Spacing

Two options are available in the specification of worksite spacing. These are random and uniform. The array holding the roadway location random numbers is arranged in ascending order. When the random option is specified, this array is used to sequentially establish the location of worksites. The simulation process is independent of activity workload with the exception of the establishment of random worksite locations.

The annual workload is used to determine the total mileage over which the simulation process will take place. This is done in the following way:

A = Annual workload per lane mile

SW = Simulation workload

L = Lanes closed

R = Random number between 0 and 1

Sta. = Worksite location mileage station

Sta. = (SW/(A x L)) x R

Where the annual workload is small relative to the simulation workload, worksites will be very far apart. As workload increases, the distance decreases because the simulation workload is constant. Also, if multiple lanes are closed then the worksites become closer together because the random site could be in any lane.

The other spacing option is uniform. In this case, a variable which describes the spacing between worksites is used to establish each worksite location. Typically, concrete joint sealing might be performed at every joint, once every three years. The spacing desired in this case would be the distance between joints.

Full Depth Concrete Patch Distribution

Based on a range of studies made by the consultant, the assumption was made that the full depth concrete patches required for a portland cement concrete pavement range from 3' x 12' to 60' x 12'. It was determined that a good frequency distribution to reflect the size of full depth concrete patches is the gamma distribution. In this function, $G(k,\lambda)$, k is a shape parameter and λ can be interpreted as a scaling parameter. The gamma distribution is for any k = 1, 2, 3, ...,

$$fs_k(x) = \frac{\lambda(\lambda x)^{k-1} e^{-\lambda x}}{(k-1)!} \quad \text{where } x \geq 0$$

X is gamma distributed with parameters k and λ. For the concrete patch size distribution it was assumed that the mean patch size would be 12' x 12'. The standard deviation for the patch was assumed to be 4' x 12'. Assuming a constant 12-foot width, the mean length of the patch is 12 feet and the standard deviation is 4 feet. By integration or, more simply, by consideration of x as the sum of k independent exponentially distributed random variables, if x is $G(k,\lambda)$, then

$$m_x = k/\lambda$$

and

$$\sigma x^2 = k/\lambda^2$$

We can solve for the k and λ values by substituting:

$$\overline{m}_x = 12$$

$$\sigma_x^2 = 16$$

$$k = 12\lambda$$

$$16 = 12\lambda/\lambda^2 = 12/\lambda$$

$$\lambda = 12/16 = .75$$

$$k = 12 \times .75 = 9$$

Therefore, where x is the length of the 12-foot wide patch, the density function for the distribution of full depth concrete patches becomes:

$$F(x) = \frac{.75(.75x)^8(e^{-.75x})}{40320}$$

A graphic plot of this distribution is illustrated in Figure 12 where a factor value of 9.6 has been applied to create an $F_x(x)$ range from 0 to 1.

Partial Depth Concrete Distribution

Based on studies conducted by the consultant, it was possible to develop a frequency distribution for the size of partial depth concrete pavement patches. A frequency distribution was plotted and again it seemed that a gamma distribution would be an appropriate shape to describe the distribution of partial depth concrete patch sizes. From the plot, it was determined to make the mean patch size three square feet and the standard deviation two square feet. We can solve for the k and λ values by substitution where:

$$m_x = 3 = k/\lambda$$

$$\sigma_x^2 = 4 = k/\lambda^2$$

$$k = 3\lambda$$

$$\sigma_x^2 = 3\lambda/x^2 = 3/\lambda$$

$$\lambda = 3/4$$

$$k = 3(3/4) = 9/4$$

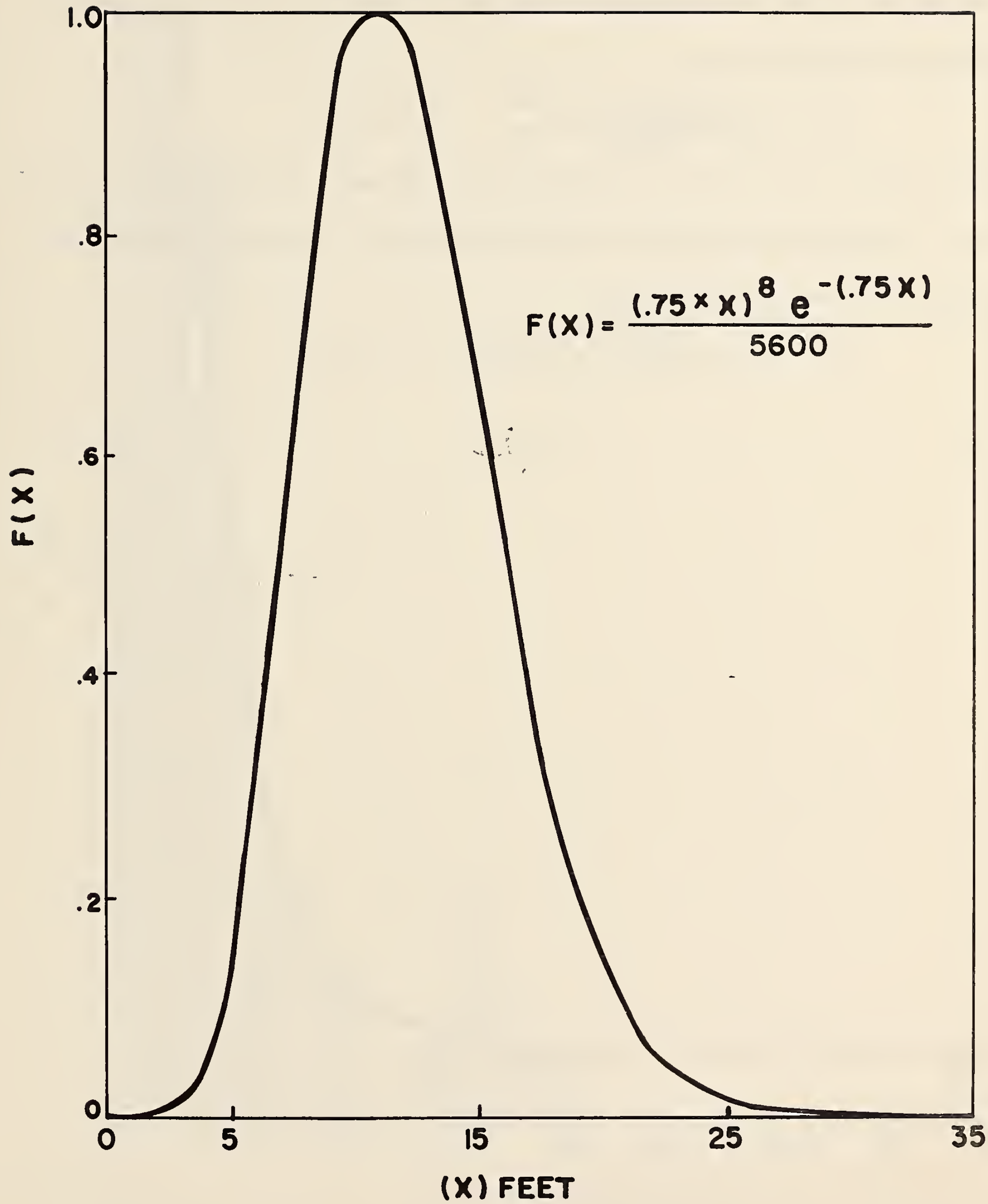


Figure 12. Frequency distribution developed for full depth concrete patching

Therefore, where x is the area of a partial depth concrete patch, the density function becomes

$$F(x) = \frac{.75(.75x)^{1.5}e^{-.75x}}{(1.5)!} \quad x \text{ Factor}$$

This function could not be expanded, but through a trial and error process, the following function was established to fit the frequency distribution shown in Figure 13.

$$F(x) = 2.2(.75x)^{1.5}e^{-.75x} + .1$$

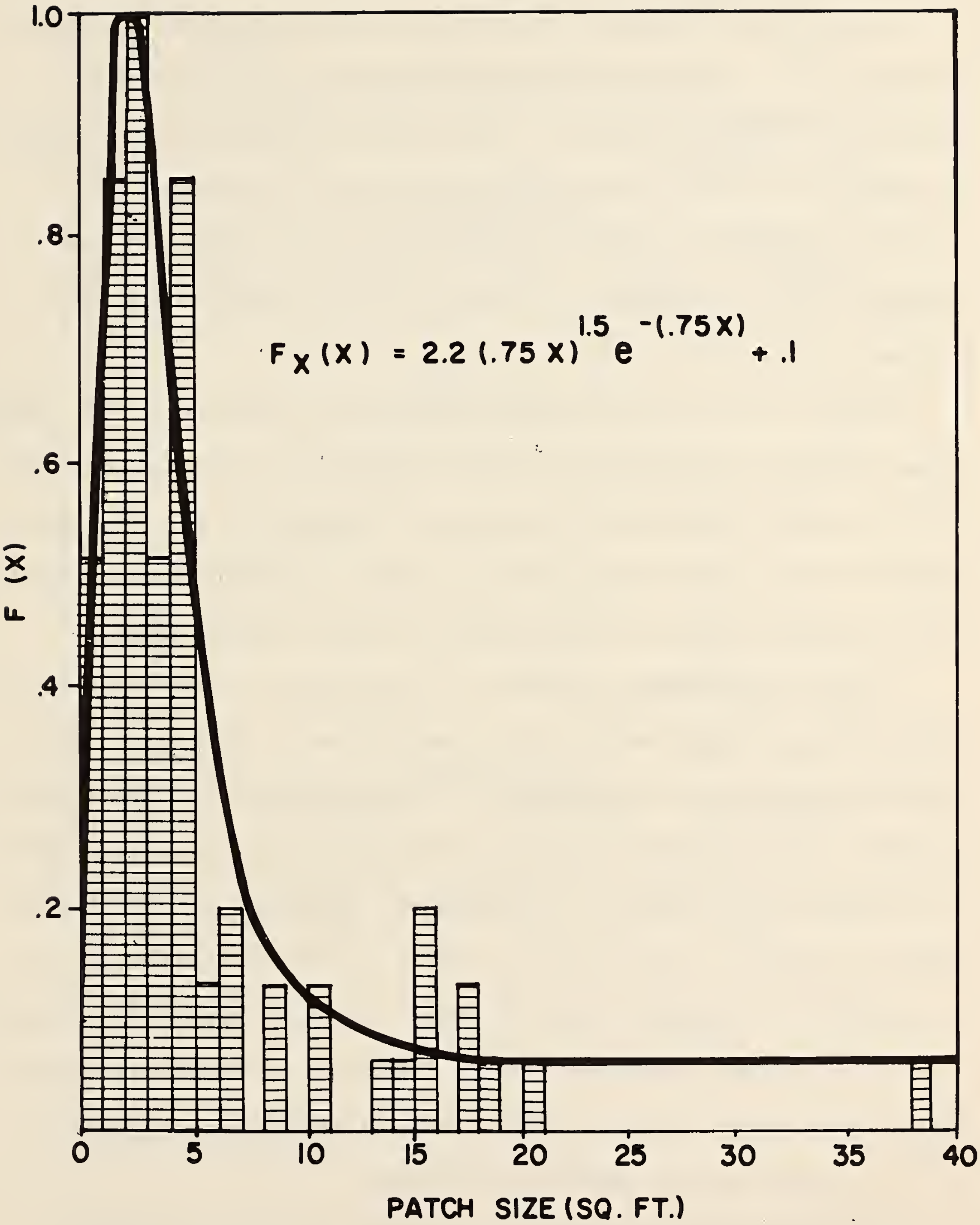


Figure 13. Frequency distribution developed for partial depth concrete patching

Performance Standards

Based on the TRB-AASHTO Joint Study of Maintenance and Operations Personnel[46], 44 of the 50 states have or contemplate having a maintenance management system or maintenance performance budget method of operations. Both of these systems make use of maintenance work activity performance standards which describe the procedures to be followed, the men, equipment and materials to be used, and the rate of production to be achieved.

Because of the wide use made of performance standards by the states, it was decided to structure the program developed for the Economic Analysis of roadway occupancy for maintenance and rehabilitation in such a way that each state could readily use their own performance standard data in the development of maintenance and rehabilitation costs.

A typical performance standard is illustrated in Figure 14. This crack filling standard shows that a five-man crew using 2 dump trucks, 1 heating kettle, and a compressor, can place 500 pounds of crack sealer per hour. This particular standard reflects the production rate which is achieved on the roadway. If a state has structured its performance standard production rate to include travel to the job site, it should be adjusted to accommodate the crew travel time specified in the program.

In the program, occupancy time is determined by simulating the performance of a crew. This simulation includes the following elements:

1. Travel time to and from the roadway
2. Time for the installation and removal of traffic control signing and delineation

State of Nevada
Department of Highways
Maintenance Division

MAINTENANCE PERFORMANCE STANDARDS

ACTIVITY NO.	ACTIVITY	ACCOMPLISHMENT UNIT
101.07	Crack Filling	Pounds Filler Material

ACTIVITY REQUIREMENTS

MEN		EQUIPMENT		MATERIALS	
NO.	CLASS	NO.	TYPE	AMOUNT	DESCRIPTION
5	Maintainers	2	Dump Trucks Single Axle	1 lb.	Crack Filler (Pounds)
		1	Asphalt Kettle (Heating)		
		1	Compressor with nozzle to clean cracks		

PRODUCTIVITY DATA

Unit/Crew Hr.	Unit/Man Hr.	Crew Hr./Unit	Man Hr./Unit
500# Filler/Crew Hr.	100# Filler/Man Hr.	0.002 Crew Hr/#Filler	0.010 Man Hr/#Filler

QUALITY GUIDE

Condition: Asphalt surfacing cracked to a point to admit penetration of water. Fill cracks when they exceed 1/4" in width.

Maintenance Level: Fill cracks and joints to level of travelled surface. Work should be done in fall.

Frequency or Workload Rate:
140 pounds of filler per mile of 24' bituminous surface.

Figure 14. Typical maintenance performance standard

3. Production work at a single work site

4. Move time between work sites

5. Material cure time on the roadway

The production rate used in the program should reflect the production which can be achieved at the work site.

The performance standard for full depth concrete patching being used as the default in the program is summarized as follows. It is based on standard time data and the resulting performance standard which was developed in conjunction with NCHRP Study 14-2 presently being reviewed by the Transportation Research Board.

Activity: Full Depth PCC Patching

Crew	Equipment	Materials
	1 Concrete Saw	Ready-mix PCC
1 Foreman	1 Water Truck	
3 Equipment Operators	1 Hydraulic Ram	
3 Laborers	1 Front End Loader	
	3 Dump Trucks	

Production Rate - 75 cubic feet per hour.

This information must be converted to fit the program format where the following elements are needed:

1. Crew hourly costs

2. Material costs per workload unit

3. Production rate in workload units per hour

The workload model in the program predicts square yards of full depth portland cement concrete patching. Therefore, both the material and production rate must be converted to reflect accomplishment units of square yards. Hourly unit costs must be applied to crew members and equipment and the accomplishment units costed for material.

Table 10 shows average hourly wage rates[46], typical equipment rental schedule[37], and typical material unit costs[37]. Unit costs from this table have been used in the example shown below to illustrate how the performance standard data is converted to fit the program format.

Activity: 9" Portland Cement Concrete Full Depth Patching

Number	Classification	Hourly Unit Cost	Hourly Cost
1	Foreman	4.63	$ 4.63
2	Equipment Operator II	3.60	7.20
1	Section Man	4.29	4.29
3	Laborers	2.86	8.58
		Total Labor	$24.70
1	Concrete Saw	1.00	$ 1.00
1	Water Truck	2.00	2.00
1	Hydraulic Ram	8.20	8.20
1	Front End Loader	5.00	5.00
2	Dump Truck	3.75	7.50
		Total Equipment	$23.70
Labor and Equipment Costs			$48.40/Hr.

Material

Ready mix @ 25.00 per cy

25 x 9/36 = 6.25/SY

Table 10. Typical hourly labor rates (46) equipment rental rates (37), and material unit costs (37)

EQUIPMENT RATES

Description	Hourly
Mileage Vehicles	$ .20
9,000 GVW Trucks (Garbage & Service)	1.75
Trucks Dump Single Axle	3.75
Trucks Dump Tandem Axle	6.50
Trucks, Tractor	6.00
Trucks, All Wheel Drive	7.25
Trucks, Flatrack	3.85
Trucks, Service (Sign Service, Boom, Lube, Drill, Mech.)	3.50
Line Stripper	11.00
Traction Broom	4.25
Street Sweeper (S.P.)	7.00
Street Flusher (Semi-Mount)	2.70
Compressors	2.75
Cranes and Fork Lifts	.50
Distributors (Truck or Semi-Mounted)	4.50
Maintenance Distributors (Pot Type to 600 Gal.)	3.00
Motor Graders	5.80
Pulvimixer	11.50
Chip Spreader Box and Windrow Sizer (Towed)	2.00
Loaders (Except Industrial Style Tractors)	5.00
Conveyors	3.50
Conveyor W/Screens	8.25
Concrete Mixers	2.80
Patcheaters (Towed)	3.00
Mowers, Rockpickers, Roto Shredders, Maintainer	7.25
Ram, Hydraulic	8.20
Rotary Plows	60.00
Rollers Pulled	.85
Rollers, Steel Wheel (Includes Vibratory)	7.85
Rollers, Pneumatic Tired	11.00
Shovel and Backhoe Combination, Truck Mounted	9.00
Welders, Trailer Mounted	2.00
Electric Plants	2.00
Water Tanks, Trailer Mounted	2.00
Tractors, Industrial W/Attachments (Loader, Auger, etc.)	3.25
Tractors, Crawlers	9.00
Snow Tractor W/Dozer	2.50
Carryall Scrapers	2.80
Rippers	1.00
Saw	1.00
Air Hammer	.50
Trailers, Cargo or Tilt	3.00
Trailers, Dump	5.25
Classrooms	15.00
Trailers, Utility	.85
Chip Spreader(S.P.)	16.00
Heater Planer, (Towed)	15.00
Screening Plants	5.50
Mobile Drill	9.00
Crushing Plant	15.00
Lab Trailers	.75
Line Striper (Small Self-Propelled)	3.00

LABOR RATES

Description	Monthly	Hourly
Gang Foreman	$803	$4.63
Section Man	743	4.29
Common Laborer	496	2.86
Skilled Laborer	652	3.76
Equipment Operator I	566	3.27
Equipment Operator II	624	3.60
Equipment Operator III	711	4.10

MATERIAL UNIT COST

Description	Units	Unit Cost
Aggregate	CY	3.14
Screenings	CY	7.28
Bituminous Mix	CF	8.64
Chlorides (Salt)	TNS	15.00
Salt and Sand	TNS	5.30
Plantmix	CY	9.00
Expansion Joint Filler Material	LBS	.30
Cement	SACKS	2.50
Concrete	CY	25.00
Liquid Asphalt	GAL	.40
Crack and Joint Filler	LB	.08
Fertilizer(Pounds)	LB	.10
Fertilizer (Gallons)	GAL	8.50
Insecticides & Herbicides (Pounds)	LB	2.00
Propane Cylinders (100 Lb)	LB	10.00
Propane (Bulk Gallons)	GAL	.35
Guide Posts	EA	2.25
Sight Plates & Guardrail Delineators	EA	.38
Marker Plates	EA	3.55
Snow Poles	EA	1.50
Signs	EA	3.85
White Paint	GAL	3.63
Glass Beads	LBS	.13
Yellow Paint	GAL	4.35
Paint Thinner	GAL	.70
Sign Posts	EA	.81
Fence Posts	EA	2.50
Fencing	LF	.20
Steel Guardrail	LF	2.30
Steel Cattleguard	EA	33.00
Culvert Pipe, 18-inch	LF	3.65
Culvert Pipe, 24-inch	LF	4.75
Culvert Pipe, 30-inch	LF	6.90
Culvert Pipe, 36-inch	LF	8.29
Culvert Pipe, 48-inch	LF	15.25
Guardrail Posts	EA	18.00

Production Rate

75 cubic feet/hour

75/(9 x 9/12) = 11.1 sq. yd. per hour

The three values needed to completely describe the activity, PCC full depth patching, have now been established. In summary they are:

1. $48.40 crew hourly costs

2. $6.25 material work unit costs

3. 11.1 SY per hour workload production rate

The activity standards used in the program are shown in Table 11 and the resulting program default matrix for the activity performance data is shown in Table 12.

Table 11. Activity performance standards developed for an economic analysis of roadway occupancy for maintenance and rehabilitation.

Activity: Partial Depth PCC Patching

Crew	Equipment	Material
1 Maint. Man	1 Air Hammer	1 lb. Cement (rapid set)
4 Laborers	1 Air Compressor	6 lbs. sand
	1 Concrete Saw	
	1 Mortar Mixer	
	1 Dump Truck	

Production Rate: 5 SF/hour

Activity: Joint Sealing

Crew	Equipment	Material
1 Maint. Man	1 Air Compressor	.26# Asphalt
3 Laborers	1 Asphalt Kettle	Joint Sealant
	1 Pouter	
	2 Dump Trucks	

Production Rate: 280 ln Feet/hour

Activity: Mudjacking

Crew	Equipment	Material
1 Foreman	2 Air Hammers	.3 Sacks cement
1 Equipment Operator	1 Water Tank	
3 Laborers	1 Mudjack	
	2 Dump Trucks	

Production Rate: 0.5 CF/minute
Minimum Workload: 50 CF

Activity: Temporary Blowup Repair

Crew	Equipment	Bituminous
1 Foreman	2 Air Hammers	Premix - 10 yards per site
3 Equipment Operators	1 Air Compressor	
3 Laborers	1 Loader	
2 Flag Men	1 Compactor	
	2 Dump Trucks	

Production Rate: 0.5 sites/hour

Activity: Bituminous Patching

Crew	Equipment	Material
1 Foreman	1 Motor Grader	1 CY Bituminous Premix
4 Equipment Operators	1 Roller	3 Gal. Liquid Asphalt
	1 Asphalt Distributor	
	2 Dump Trucks	
	1 Loader	
	1 Low Boy	

Production Rate: 10 CY/hour

Activity: Bituminous Base and Surface Reoair

Crew	Equipment	Material
1 Foreman	1 Motor Grader	.67 CY Aggregate
3 Operators	1 Loader	.33 CY Bit. Premix
4 Laborers	1 Roller	1/3 Gal. Liquid Asohalt
	1 Water Trailer	
	1 Asphalt Distributor	
	1 Low Boy	
	3 Dump Trucks	

Production Rate: 5.6 CY/hour

Activity: Crack Sealing

Crew	Equipment	Material
1 Maint. Man	2 Dump Trucks	.3 lb. Crack Filler
4 Laborers	1 Asphalt Kettle	
	1 Compressor	

Production Rate: 500 ln feet/hour

Table 12. Maintenance Activity Performance Standard Data used as defaults in the program.

Activity	Workload Units	Labor & Equipment	Material	Production Rate
Full depth PCC Patching	sq. yds.	$48.40/Hr.	$ 6.25/SY	11.1 SY/Hr.
Partial depth PCC Patching	sq. ft.	$31.92/Hr.	$ 0.20/SF	5 SF/Hr.
Blowups	Sites	$48.98/Hr.	$86.40/Site	.5 Sites/Hr.
Mudjacking	cu. ft.	$35.91/Hr.	$ .70/CF	30 CF/Hr.
Joint Sealing	ln. ft.	$26.62/Hr.	$ .075/LF	280 LF/Hr.
Bituminous Patching	sq. yds.	$55.83/Hr.	$ .50/SY	180 SY/Hr.
Bituminous Base and Surface Repair	cu. yds.	$69.42/Hr.	$ 5.07/CY	5.6 CY/Hr.
Bituminous Crack Sealing	ln. ft.	$28.98/Hr.	$ .10/LF	1500 LF/Hr.
Resurfacing	sq. yds.	---	$ 1.20/SY	700 SY/Hr.

MOTORIST MODULE

The motorist impacts due to roadway occupancy include operation costs, loss time, changes in accident potential and pollution emissions. To effectively evaluate these impacts requires the development of the following information:

1. The hourly volume of traffic on the roadway by direction
2. The composition of the hourly volume by trip purpose
3. The average highway speeds during normal conditions
4. The average highway speeds, speed changes and delays created by a roadway occupancy
5. The accident potential under normal and restricted operation
6. Pollution emission rates as a function of average highway speed
7. Vehicle operation costs as a function of speed and vehicle weight for freeway alignment
8. Value of loss time
9. Accidents and cost under normal and roadway occupancy conditions

The development of this required information has been divided into speed, traffic, operation cost, value of time, accidents, and pollution.

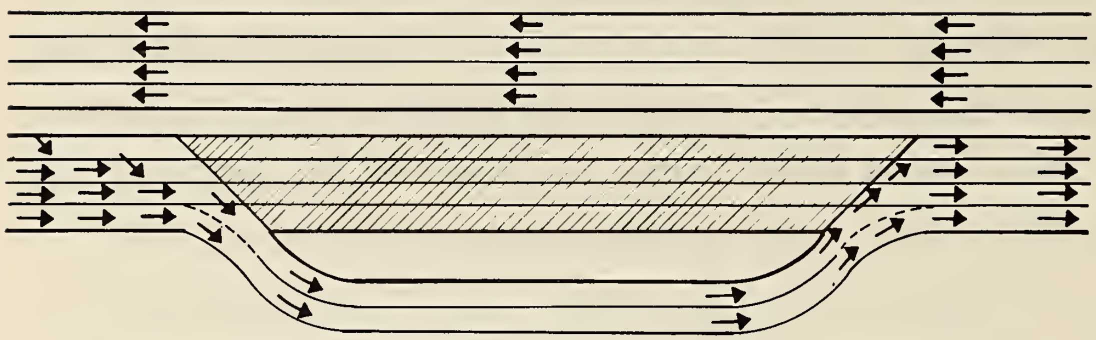
Most of the information needed to analyze motorist impacts on a given freeway segment will be unique for that segment. This includes traffic, roadway occupancy constraints, and the freeway design.

In the development of a computer program to perform the economic analysis of roadway occupancy, it was decided to structure the program to accommodate local conditions. This was accomplished by designing optional input provisions for the program. However, basic informational elements needed to be incorporated directly into the program, therefore, all data needed to execute the program was assigned through data statements. These program default values will be used in the execution of the program unless a user elects to input and override the default values.

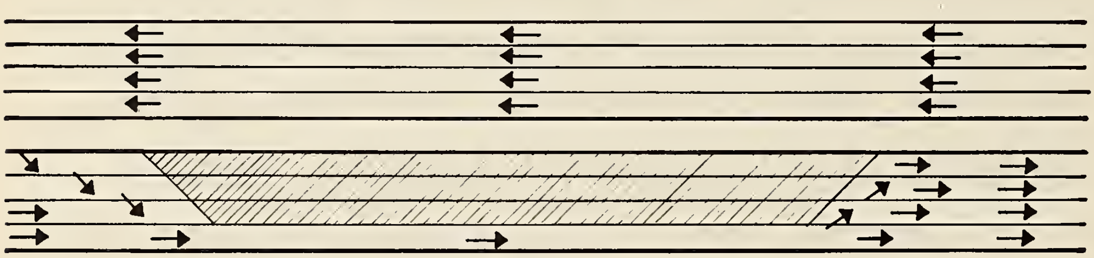
The program is designed to perform a complete economic analysis for each applicable work activity annually by roadway direction. Further, every feasible roadway closure sequence is considered. The number of roadway closure options available depends on the freeway lanes. The configurations considered by the program are illustrated in Figures 15 through 19. In Figure 15 and 16, the lane closures possible with an eight-lane divided roadway are illustrated. These include four lanes closed and traffic detoured to two lanes in Figure 15-A, three lanes closed in 15-B, two lanes closed in 15-C, one lane closed in 16-A and four lanes closed with traffic crossover to two lanes in opposition direction in 16-B. The user also can specify the use of either one or two shoulders which increases the capacity for each feasible lane closure and provides an additional option to traffic when all lanes are closed.

In the economic analysis of roadway occupancy, different closure strategies are examined. A strategy consists of a sequence of lane closures which has been designated a closure category for purpose of the economic analysis. The feasible closure categories available for use with an eight-lane freeway where shoulder use is not permitted are as follows:

A. 4 lanes closed, Detour



B. 3 lanes closed



C. 2 lanes closed

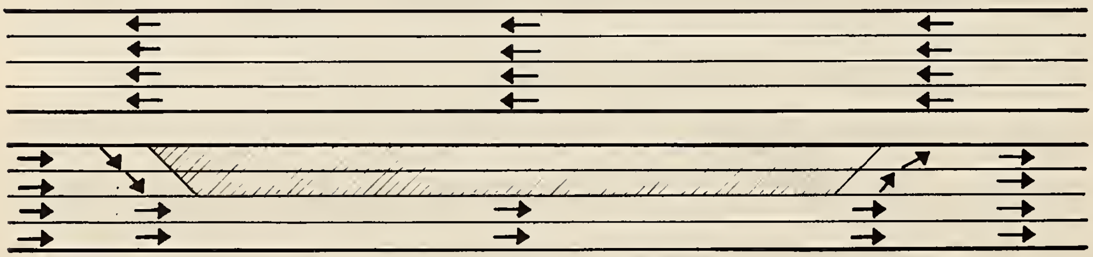
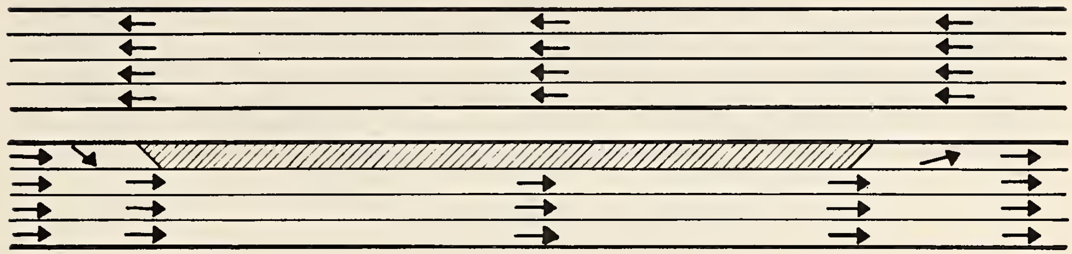


Figure 15. Four, three and two lane closures on an eight-lane freeway

A. 1 lane closed



B. 4 lanes closed, crossover

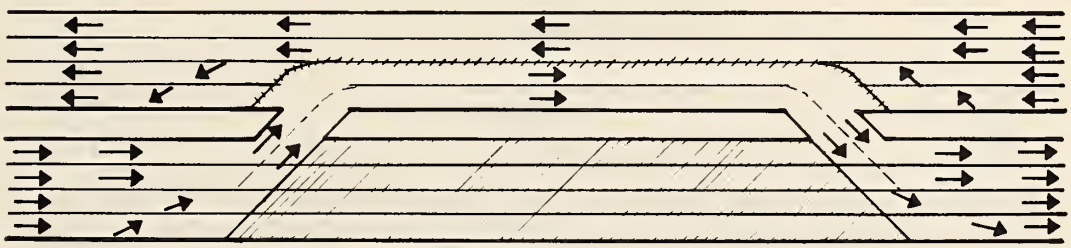
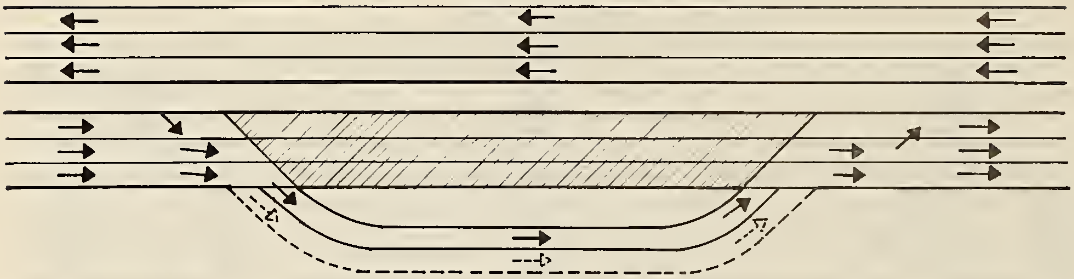
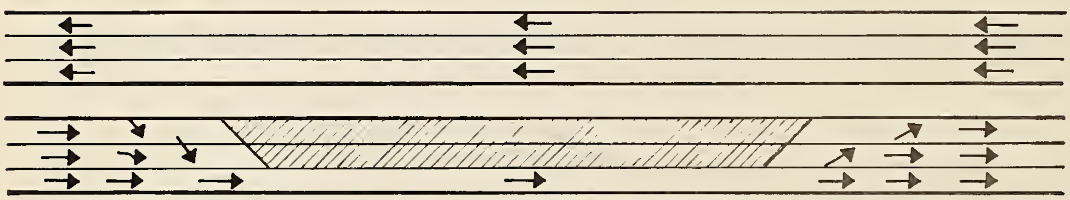


Figure 16. One-lane closure and a four-lane closure and crossover on an eight-lane freeway

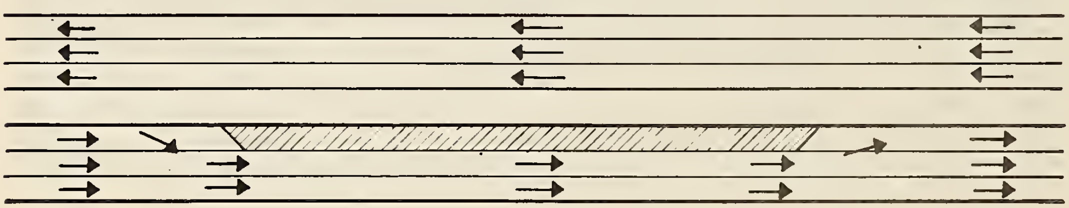
A. 3 lanes closed, detour



B. 2 lanes closed



C. 1 lane closed



D. 3 lanes closed, crossover

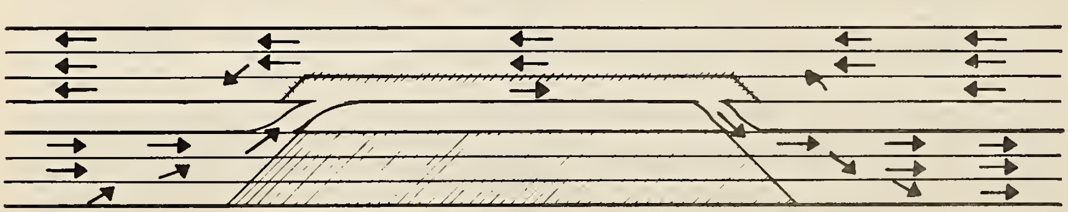
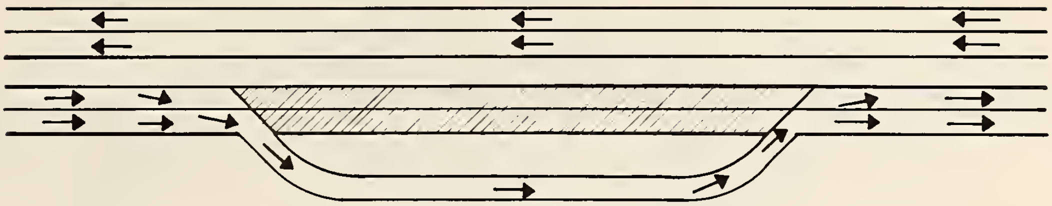
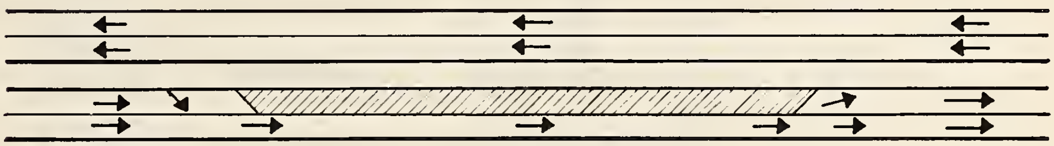


Figure 17. Three, two and one lane closure, together with a crossover for a six-lane freeway

A. 2 lanes closed, detour



B. 1 lane closed



C. 2 lanes closed, crossover

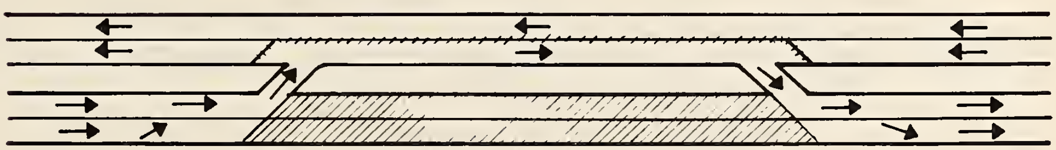


Figure 18. Two and one lane closure together with a crossover for a four-lane freeway

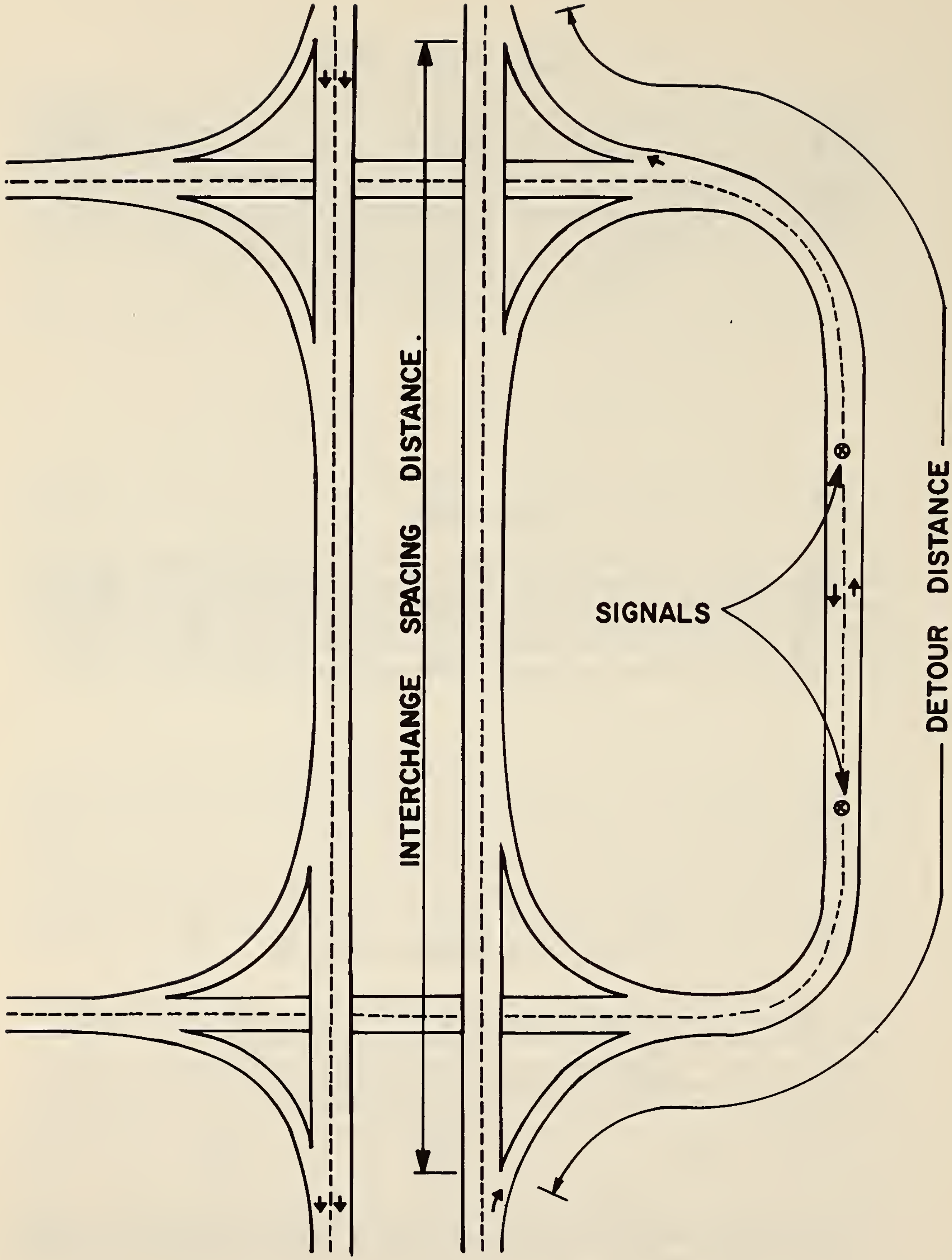


Figure 19. All directional lanes closed and a detour used for traffic.

Closure Category No. 1 = Four directional lanes closed and traffic diverted to a detour.

Closure Category No. 2 = Three, then one, directional lane closed.

Closure Category No. 3 = Two, then two, directional lanes closed.

Closure Category No. 4 = One directional lane closed at a time.

Closure Category No. 5 = Four directional lanes closed and traffic crossed over to two opposite directional lanes.

When shoulders are specified as being available, the detour option is not used; rather, four directional lanes are closed and traffic operates on the shoulder. This change in Closure Category No. 1 applies for the specification of either one or two shoulders.

A similar set of closure categories is applicable to the six- and four-lane divided highway. In the analysis process all feasible closure categories are examined for a given freeway. In support of a pavement systems design, only the closure category which produces the minimum direct activity and motorist costs for each activity is used in the generation of total roadway occupancy costs.

Speed

The most critical component of the economic analysis of roadway occupancy is the change in operating speed of vehicles on a freeway during the occupancy period.

An extensive field data collection program was designed and implemented in an effort to adequately quantify the behavior of traffic during roadway occupancy conditions.

The field data collection procedures were designed to develop speed profiles on a wide range of closure conditions for operation on 4-, 6-, and 8-lane freeways. The mechanics of the collection effort were automated as much as possible to improve the reliability of the data developed and to expedite data reduction efforts.

Instrumentation

A simple oscillator was built to be attached to a test vehicle's speedometer. The oscillator was housed in a small box and was powered by the car's battery. The oscillator generated three different frequency signals, which were monitored using a small, inexpensive portable cassette tape recorder. The middle frequency was used to signify that a test was in progress on the tape. This middle frequency is illustrated in Figure 20 as the test frequency.

A low frequency signal was generated for each rotation of a shaft attached to the frequency box. The shaft through an extension was attached directly to the speedometer cable using a T connector. This speedometer-excited frequency signal was a function of the speed

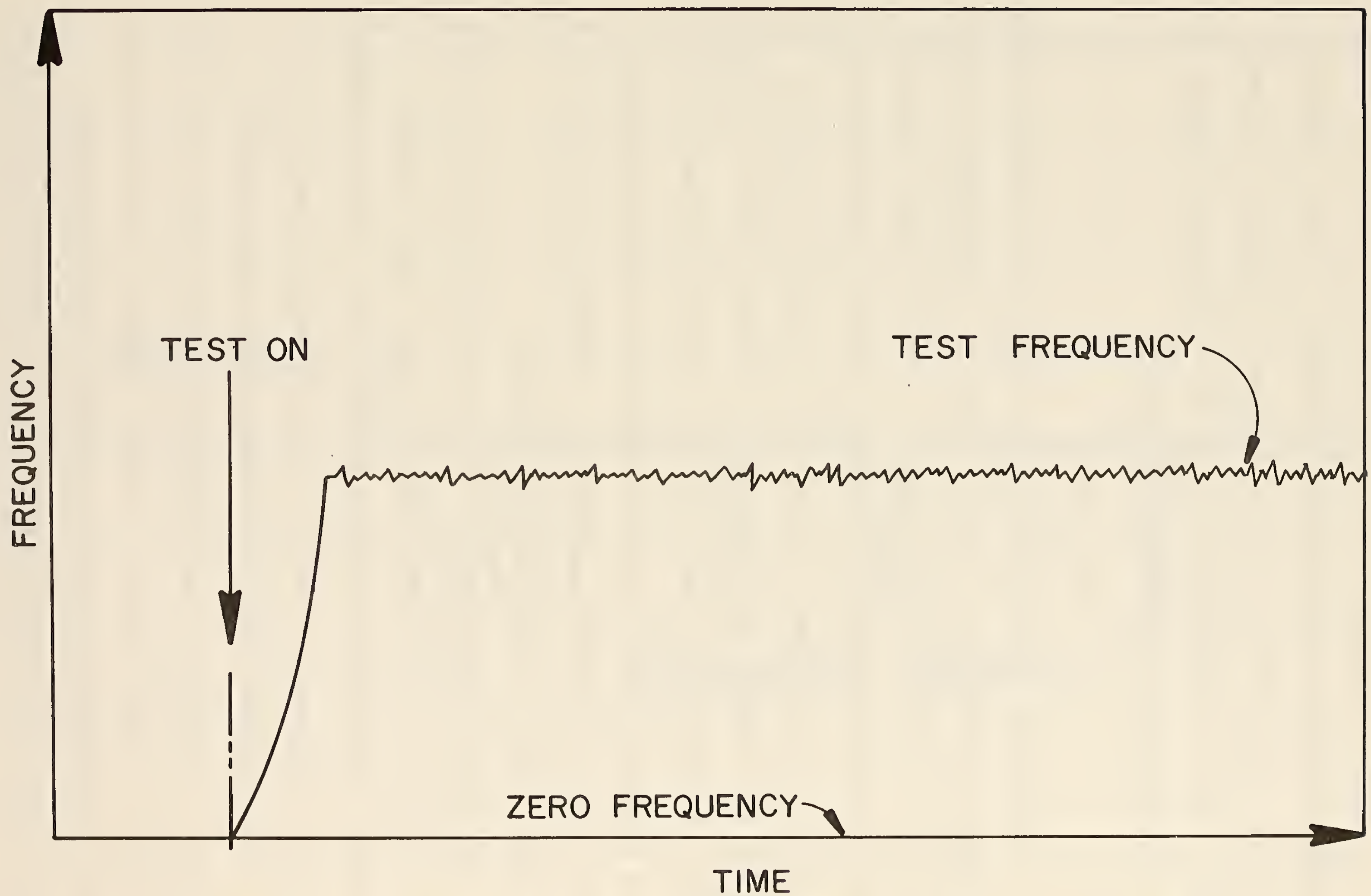


Figure 20. Schematic of the test frequency generated by the oscillator box

of the vehicle and is illustrated in Figure 21. Finally, the third signal was controlled by the vehicle driver and served as an event marker. This is illustrated in Figure 22. The circuit diagram for the oscillator box is included in Appendix A.

Field Study

In developing speed profile data, a test vehicle normally operated between interchanges. The test period was approximately 45 minutes, being controlled by the length of the tape recorder cassette tape. The test frequency was turned on after the tape recorder was running and the speedometer frequency was switched on just prior to entering the freeway. Both frequencies were left on for the duration of the cassette recorder tape. The test vehicle driver made repeated passes through the traffic control zone noting with his event frequency switch the location of observers stationed at both ends of the work zone. This is illustrated in Figure 23.

The observers were placed at each end of the work zone and also were equipped with oscillator boxes and cassette tape recorders. The observers' function was to develop traffic counts, vehicle headways and lapsed time data for vehicles passing through the work zone.

The oscillators used by the observers had three switches; a middle test frequency, a low frequency for normal events and a high frequency for control events. The test frequency, as with the test vehicle, was needed to signal the presence of test data on the cassette tape. The normal event switch was excited for each passing

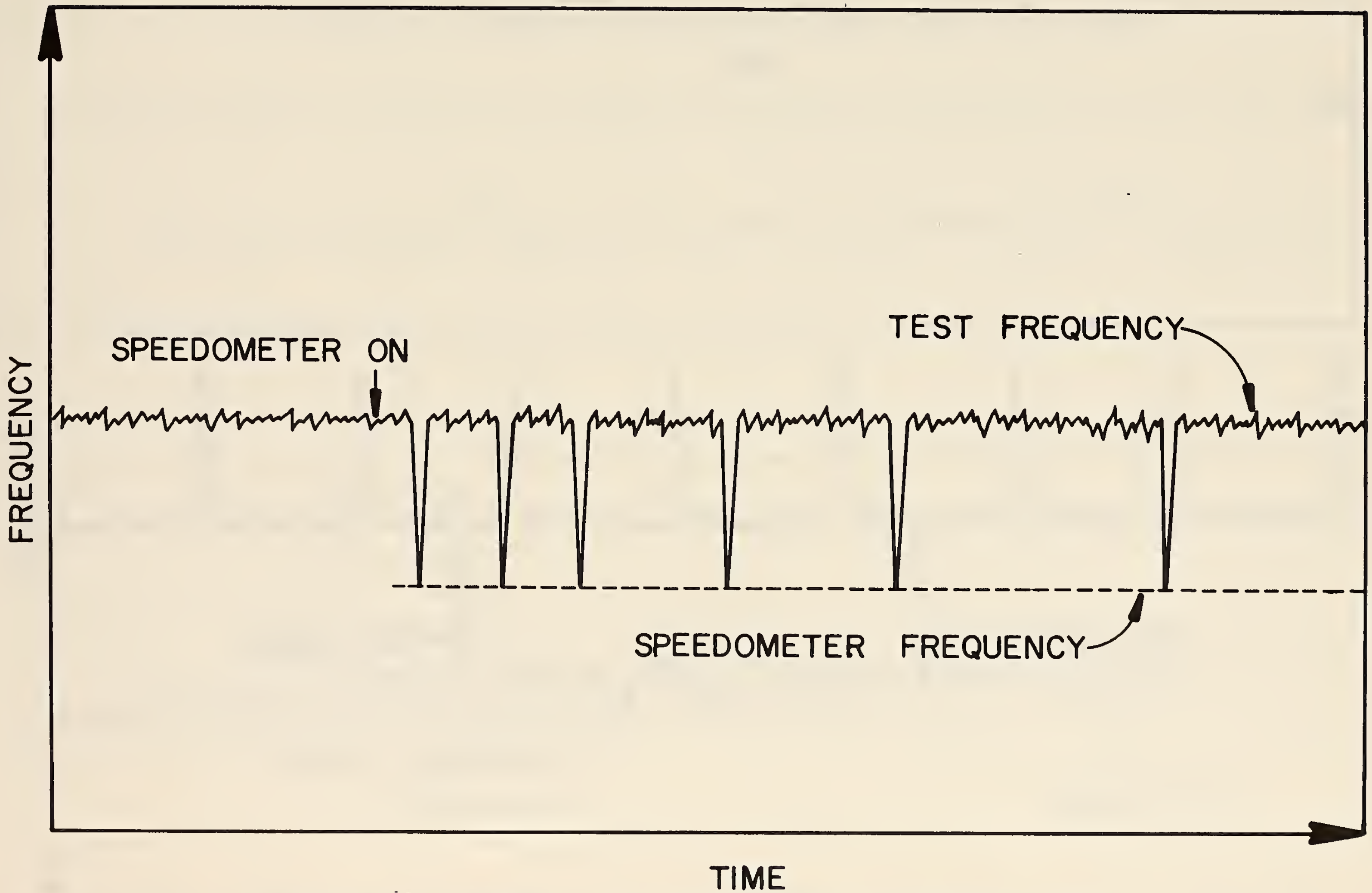


Figure 21. Schematic of the low frequency speedometer signal

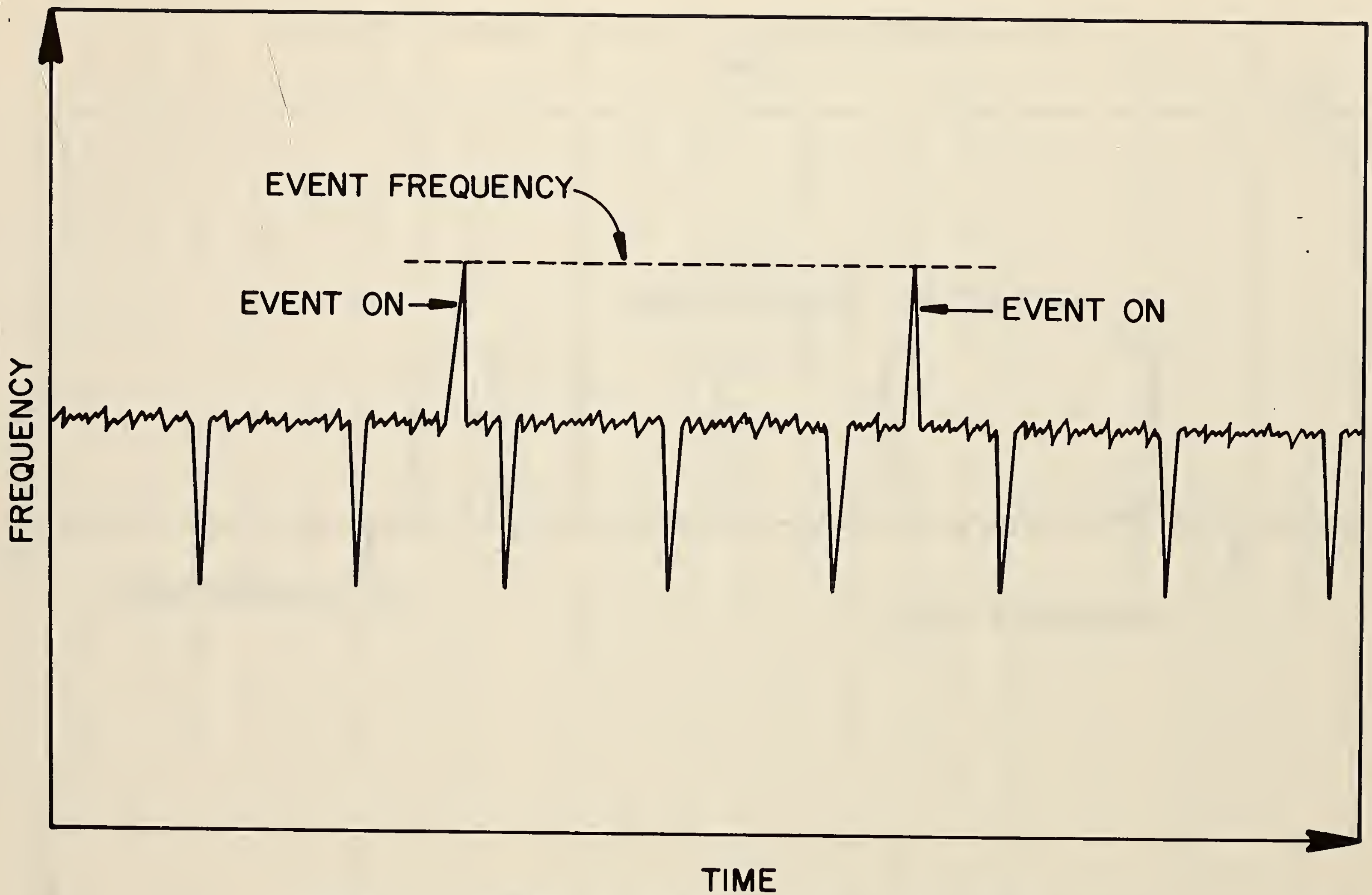


Figure 22. Schematic of the high frequency event marker signal

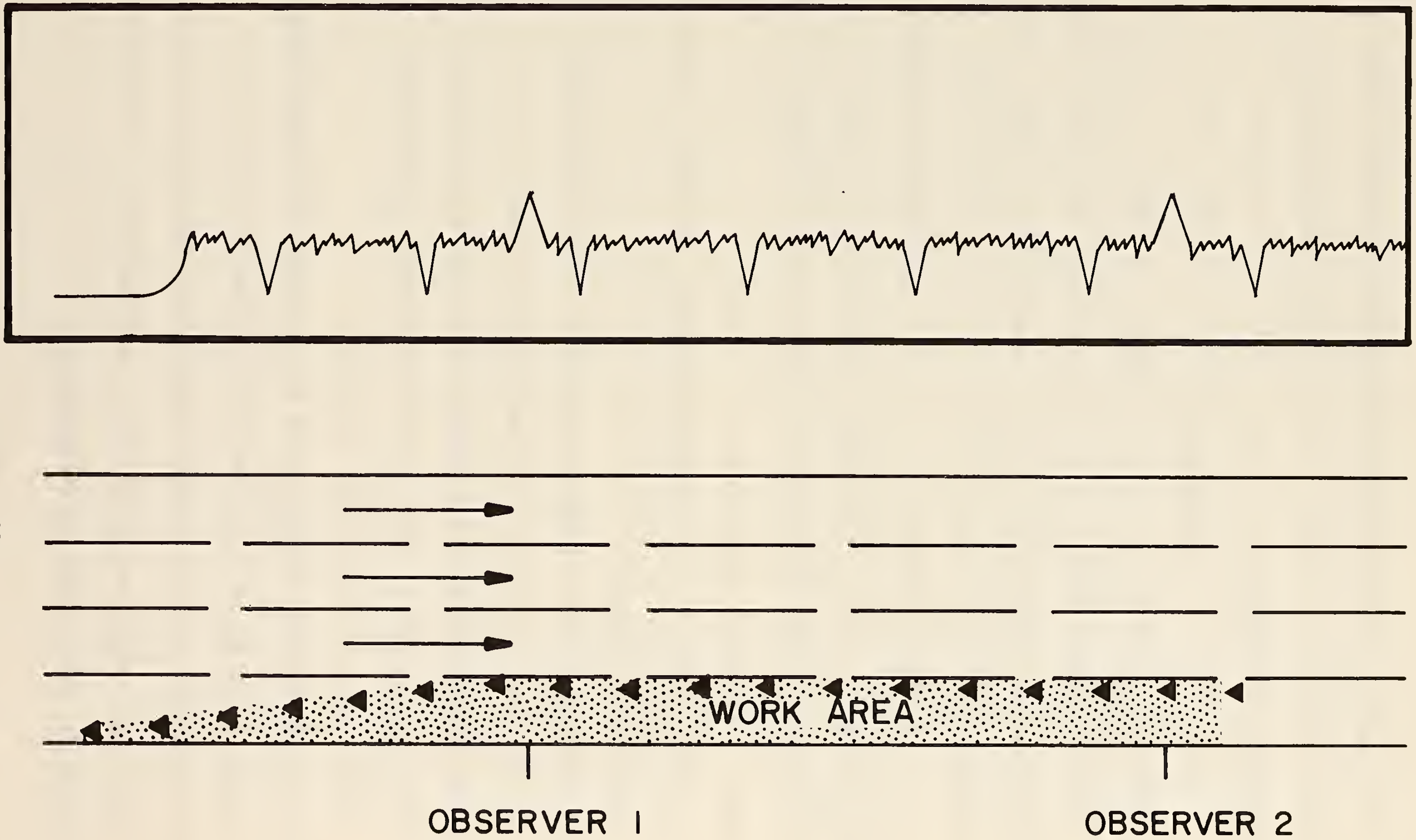


Figure 23. Schematic of signals generated on the cassette tape during a typical test vehicle profile run through a work zone

vehicle. The control event was used to record the passing of the test vehicle which permitted the data collected by the test vehicle and by observers to be coordinated.

Date Reduction

The field data collection effort produced a series of cassette tapes. Each tape represented a time continuum with two types of events. The next step was to convert this tape information into a form which could be interpreted into speed profiles, lapse times and traffic volume.

The data from the cassette tapes was consolidated onto tracks of a ¼-inch tape reel. These ¼-inch reels were processed through an analog computer to create a digital readout of times for each frequency event on the tapes. This was accomplished as follows:

1. A program board was designed to identify the three frequency signals on the tape.
2. A time pulser was set to output 1/100 of a second signals which were counted by an accumulator and held.
3. The ¼-inch tape reel was processed at a constant rate by the analog computer and every frequency signal above or below the test signal was identified.
4. As each signal was sensed, it was assigned the value of the accumulated number residing in the pulse hold area.
5. The numbers for frequency signals above the test frequency were made negative to differentiate them from the frequencies signals below the test frequencies.

6. The resulting digital numbers were placed in a file on a digital computer tape.

Once the conversion to digital tapes was complete, it was necessary to develop computer programs to convert the digital data to speed profiles, volumes and lapse time data. A speed was developed for every second of lapse time. A typical computer generated table of speeds is shown in Table 13. This provided about a 1% accuracy for the speed profiles. The volume data was structured to reflect hourly volumes at intervals of 1, 2, 3, 4, 5, and 10 minutes. A typical volume printout is illustrated in Table 14. The lapse time data proved unreliable due to processing discrepancies at the tape boundary areas.

Speed Profiles

Speeds were computed by a data processing program in miles per hour for stationing along a roadway. A negative stationing value was used to tie the profile to actual physical locations on the roadway. This permitted plots to be made of actual speed profiles through the traffic control zones. Typical plots are illustrated in Figures 24 through 27.

Highway organizations normally have restrictions on the hours of the day a road can be occupied. As a result, most of the speed profiles were collected during moderate traffic volume conditions. Figure 24 shows the profile of speeds when two lanes out of four on an eight-lane freeway were blocked. A slight drop in the speed is discernible but it

Table 13. Example of computer generated speeds developed from field tapes

```
PREMIUM PAVEMENTS              WSDA PROJECT 121930
FIELD DATA REVIEW
SECTION NUMBER 5011  DATE 338   TIME OF DAY 1151
RURAL REGION
LOCATION: I-95 SB ST. RTE. 619 TO 610 STAFFORD, VA
```

FROM STA	TO STA	TIME	DISTANCE	SPEED
8370	8438	101	67	45
8438	8494	103	56	36
8494	8550	102	56	36
8550	8600	101	50	33
8600	8657	102	56	36
8657	8713	106	56	34
8713	8758	102	44	29
8758	8797	103	39	25
8797	8842	123	44	23
8842	8887	113	44	25
8887	8926	106	39	24
8926	8965	125	39	21
8965	9016	114	50	29
9016	9066	105	50	32
9066	9128	105	61	39
9128	9195	105	67	42
9195	9246	105	50	32
9246	9279	105	33	21
9279	9318	104	39	25
9318	9358	163	39	15
9358	9391	104	33	21
9391	9419	119	28	15
9419	9453	106	33	21
9453	9498	111	44	26
9498	9548	102	50	33
9548	9593	101	44	29
9593	9655	102	61	40
9655	9717	110	61	37
9717	9773	102	56	36
9773	9823	111	50	30
9823	9885	119	61	34
9885	9952	102	67	44
9952	10008	111	56	34
10008	10070	102	61	40
10070	10132	102	61	40
10132	10188	102	56	36
10188	10255	102	67	44
10255	10317	100	61	41
10317	10384	100	67	45
10384	10457	100	72	49
10457	10536	106	78	49
10536	10614	106	78	49
10614	10670	105	56	36
10670	10721	103	50	32
10721	10783	118	61	34
10783	10833	104	50	32
10833	10889	116	56	32
10889	10945	100	56	38
10945	11001	109	56	34
11001	11063	106	61	38

Table 14. Computer printout of computed hourly volumes at a test site used to develop speed profiles.

PREMIUM PAVEMENTS WS&A PROJECT 121930
FIELD DATA REVIEW
SECTION NUMBER 2009 DATE 331 TIME OF DAY 1540
RURAL REGION
LOCATION: I-95 SB ST. RTE 61C TO FALMOUTH STAFF.VA

	EXPANDED HOURLY VOLUME					
MINUTE NO	1 MINUTE	2 MINUTE	3 MINUTE	4 MINUTE	5 MINUTE	10 MINUTE
1	900	0	0	0	0	0
2	960	930	0	0	0	0
3	1380	1170	1080	0	0	0
4	360	870	900	900	0	0
5	780	570	840	870	876	0
6	1380	1080	840	975	972	0
7	1200	1290	1120	930	1020	0
8	900	1050	1160	1065	924	0
9	720	810	940	1050	996	0
10	1260	990	960	1020	1092	984
11	900	1080	960	945	996	984
12	1140	1020	1100	1005	984	1002
13	1080	1110	1040	1095	1020	972
14	1140	1110	1120	1065	1104	1050
15	1140	1140	1120	1125	1080	1086
16	1080	1110	1120	1110	1116	1056
17	900	990	1040	1065	1068	1026
18	1500	1200	1160	1155	1152	1086
19	720	1110	1040	1050	1068	1086
20	1440	1080	1220	1140	1128	1104
21	1080	1260	1080	1185	1128	1122
22	900	990	1140	1035	1128	1098
23	1140	1020	1040	1140	1056	1104
24	840	990	960	990	1080	1074
25	1380	1110	1120	1065	1068	1098
26	1440	1410	1220	1200	1140	1134

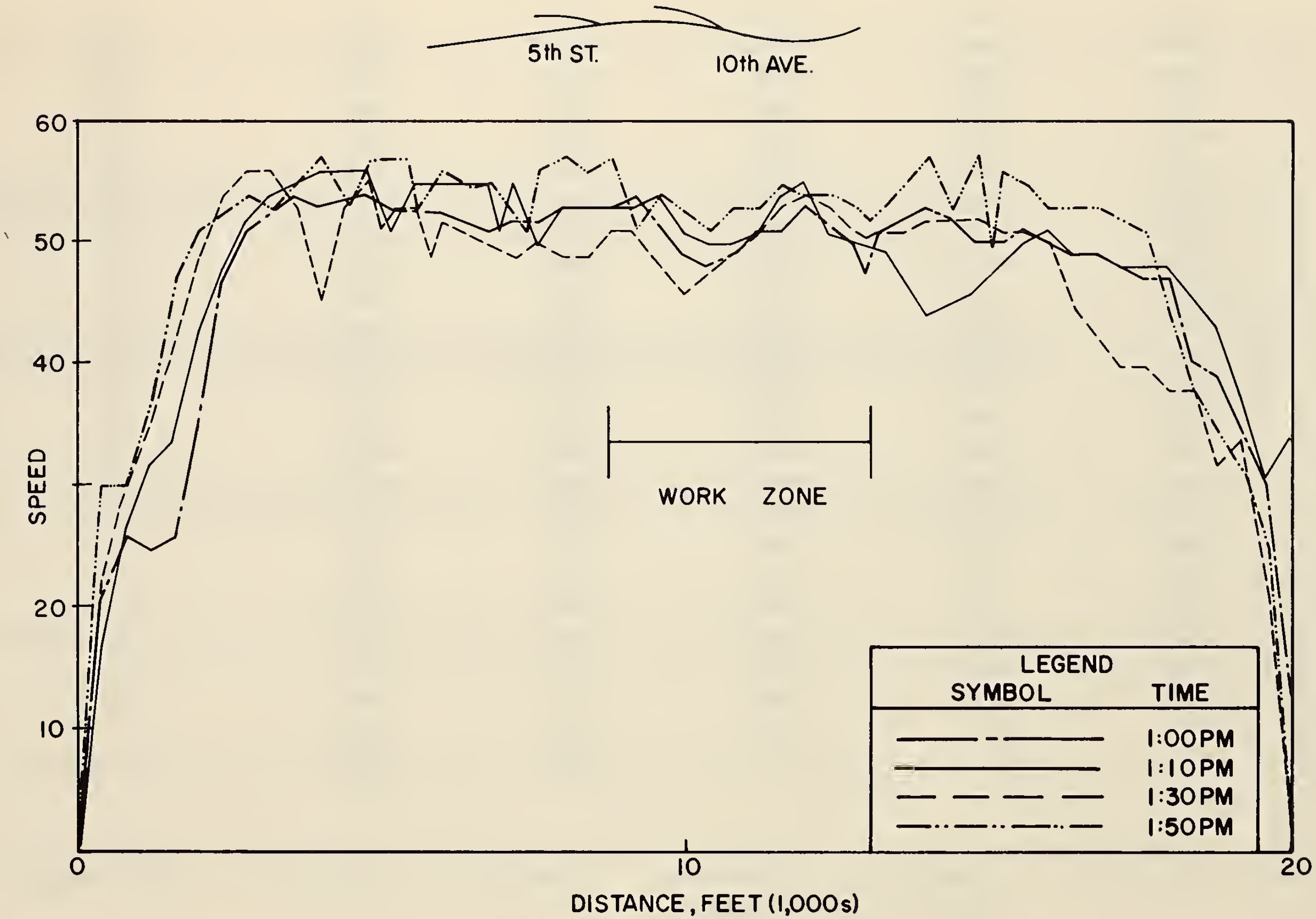


Figure 24. Speed profiles developed between 1 and 2 P.M. on an eight-lane freeway where two out of four lanes were closed to traffic in the P.M. Peak direction

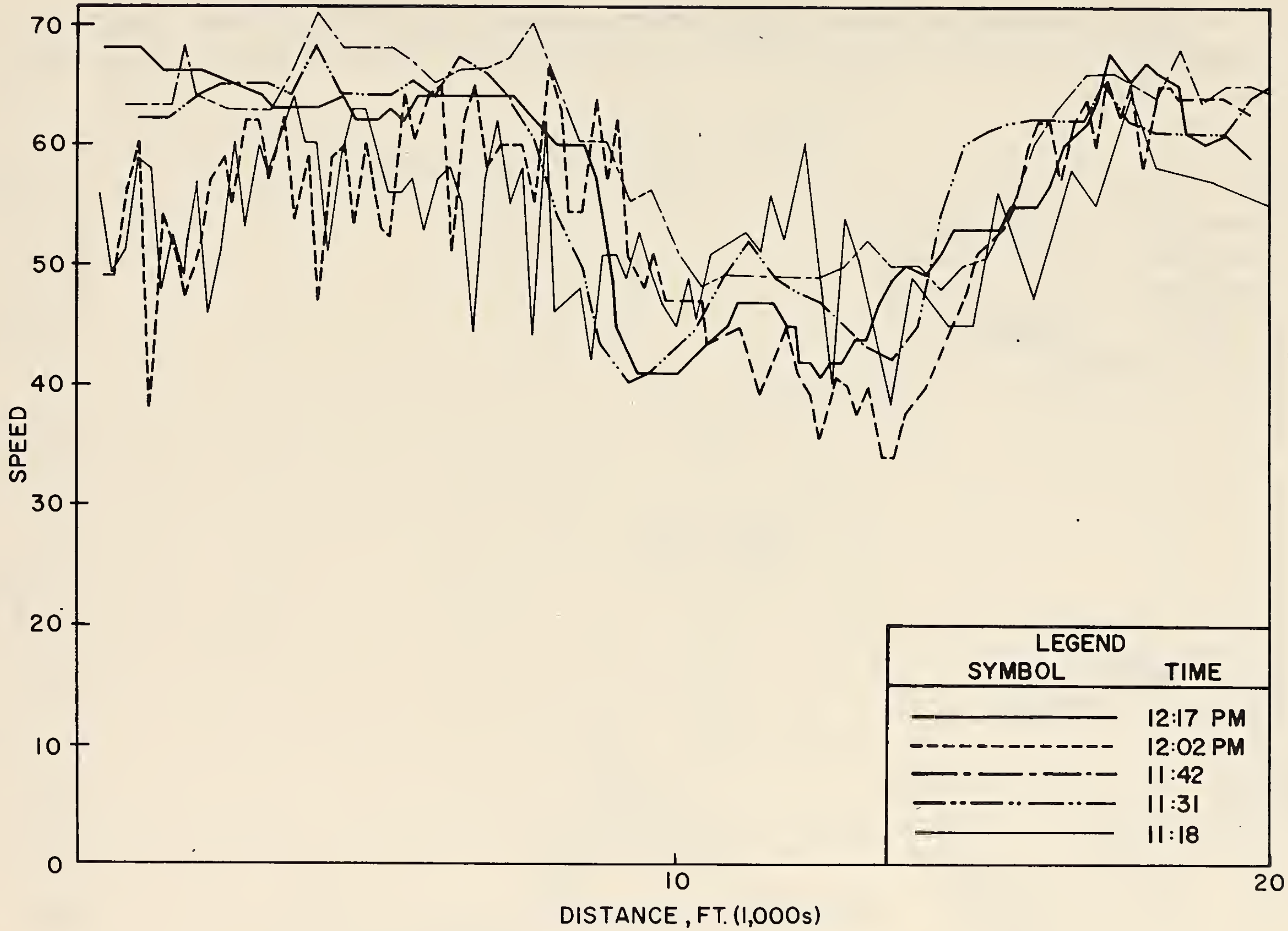


Figure 25. Speed profiles developed between 11 A.M. and 1 P.M. on a six-lane freeway where two out of three directional lanes were closed to traffic in the P.M. peak direction

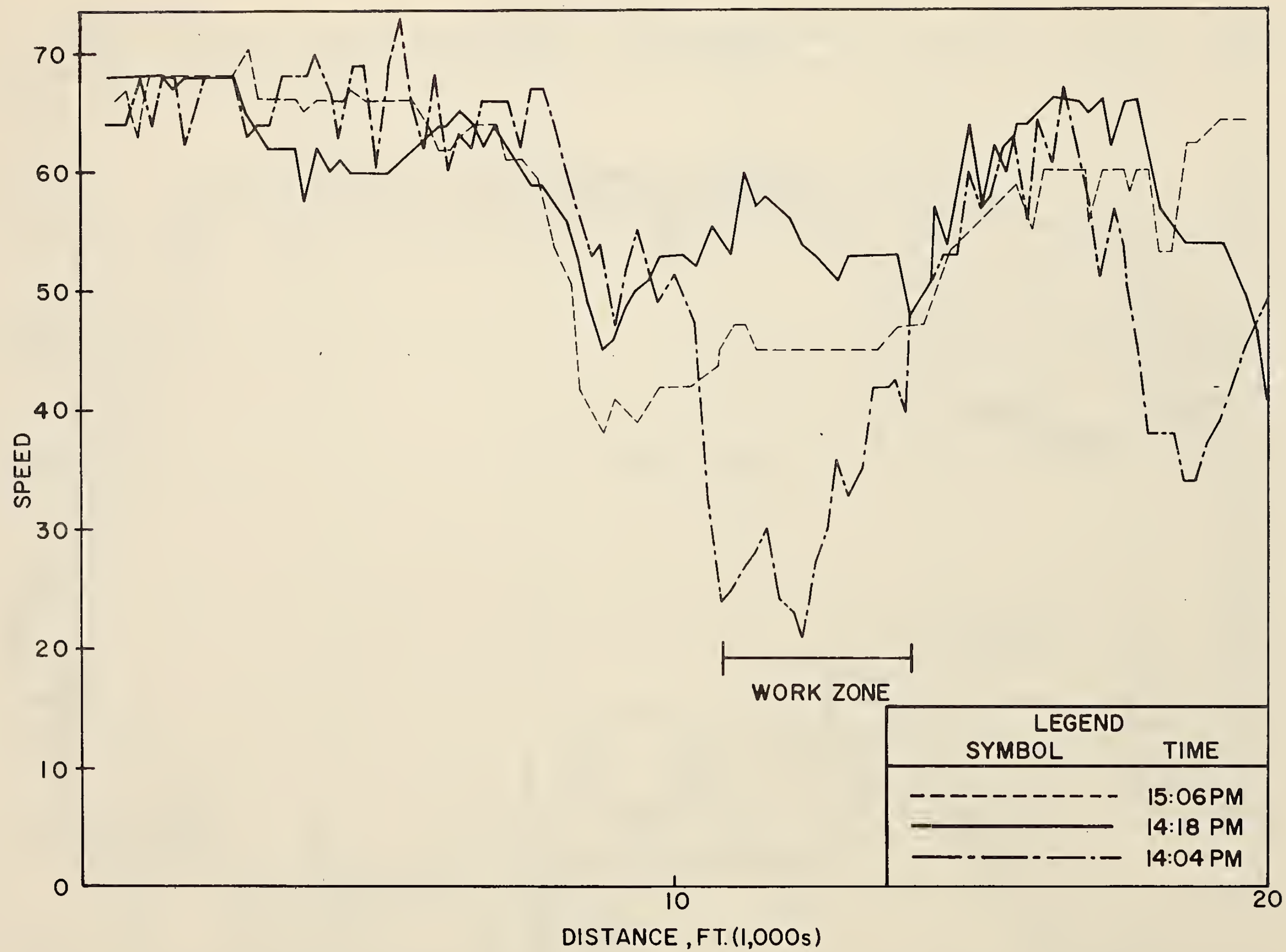


Figure 26. Speed profiles developed between 2 and 3 P.M. on a six-lane freeway where two out of three directional lanes were closed to traffic in the P.M. peak direction

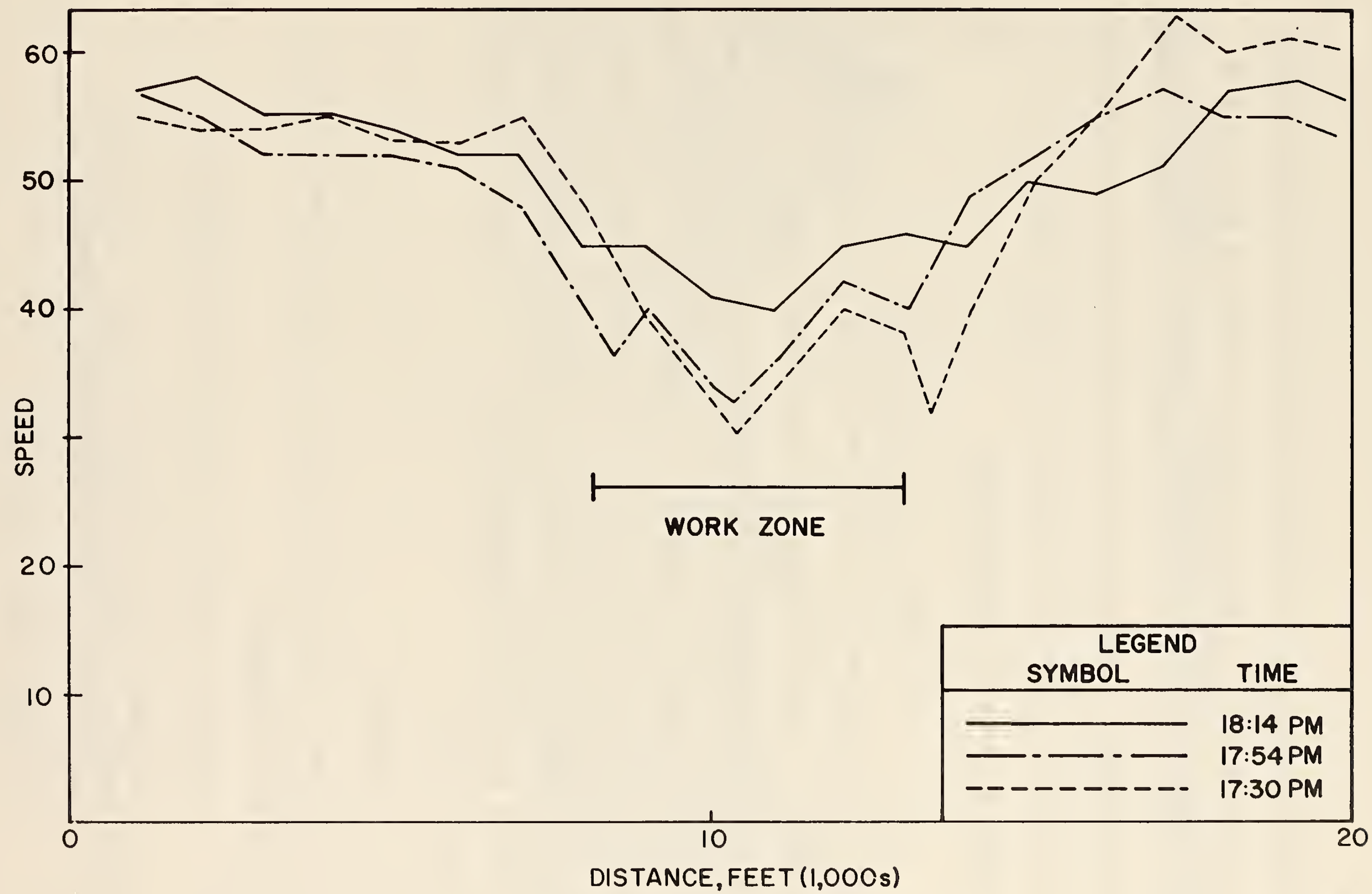


Figure 27. Speed profiles developed between 5 and 7 P.M. on a four-lane freeway where one out of two directional lanes were closed to traffic in the P.M. peak direction

is nominal.

In Figures 25 and 26, a two-lane closure on a six-lane divided facility is illustrated. The period covered from 11 A.M. to 3 P.M. The control zone was in the P.M. peak direction. As volumes increased in the late afternoon, the impact of the closure grew more pronounced. The profile shown in Figure 27 is typical of a four-lane facility where one lane is closed for maintenance.

Traffic Zone Assumptions

Based on the speed profiles developed during the study, a profile configuration for a traffic control zone was established. It is illustrated in Figure 28. Traffic is assumed to operate at approach speed (AS) up to point B, travel through the influence zone at speed ZS, and then return to speed AS on the freeway. The transition speed from A to B and from B to C and D to E are assumed to make up a speed change cycle. The magnitude of the speed change SC is equal to 1.5 times the speed difference (AS - ZS) or

$$SC = 1.5(AS-ZS)$$

When a determination is made of the change in vehicle operation cost, it consists of the following:

CN = Operation cost for a vehicle going through the influence zone at speed AS

CR = Operation cost for a vehicle going through the influence zone at speed ZS

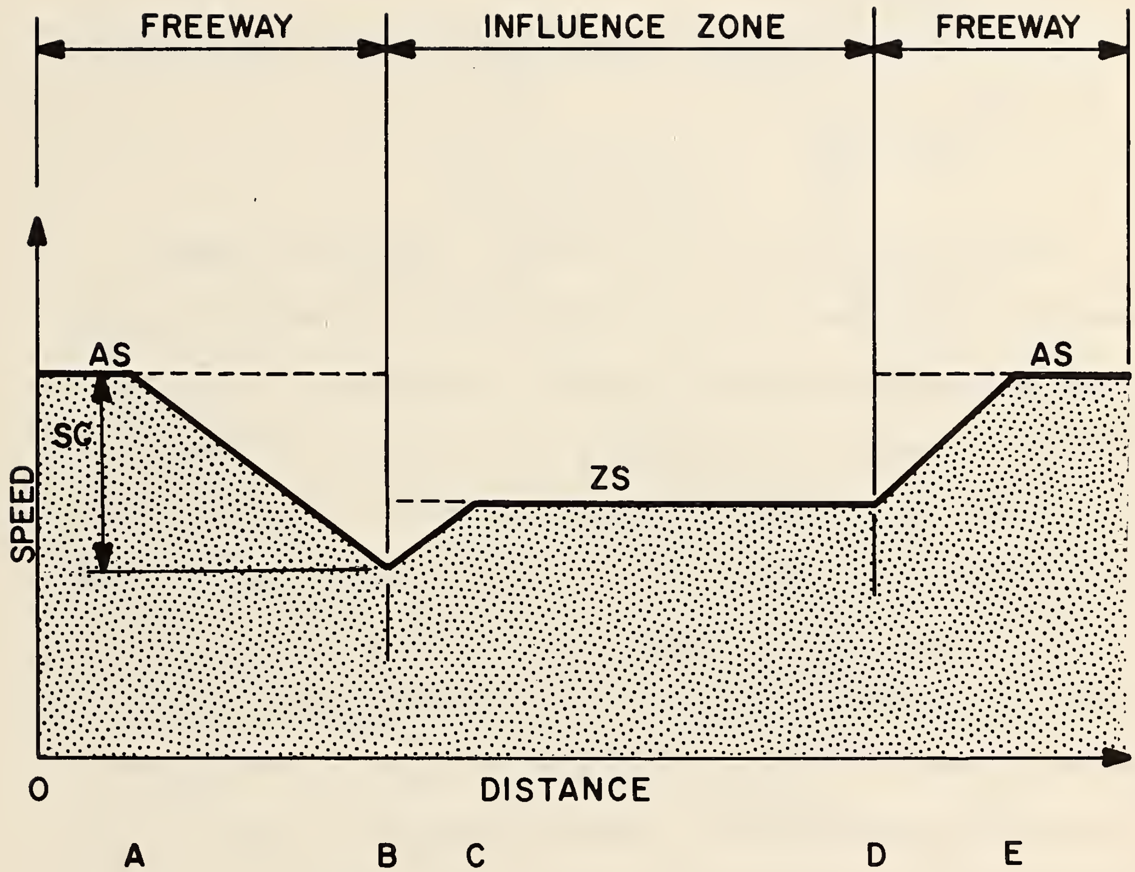


Figure 28. Schematic speed profile of unqueued traffic operation through a traffic control zone

CSC = Speed change cost for a vehicle to decrease from an initial speed of AS to a speed (AS-SC) and return to speed AS

OC = Operation cost change resulting from traffic closure

OC = CR + CSC - CN

Queue Assumptions

It was not possible to find a traffic closure that created a queue on a freeway so a series of profile runs were made in a queue situation created by rush hour traffic. In Figure 29 the traffic entering the freeway at the Route 23 interchange creates the queue and in Figure 30 the queue is created by Route 66 traffic. It may be observed that at some point in the queue, traffic comes to a stop or nearly stops. For this reason, it was assumed that if a queue is created by a traffic control zone, the speed change will be the Approach Speed AS. This is illustrated in Figure 31 where a queue is on the verge of occurring. The queue profiles as shown in Figures 29 and 30 suggested that a mean speed between zero and the speed in the influence zone would be a reasonable approximation of the average operation speed in the queue. This is shown as speed QS in Figure 32. When a queue situation exists, the computation of the operation cost change resulting from the traffic closure requires the following steps:

CQN = Operation cost for a vehicle going through the queue zone at speed AS

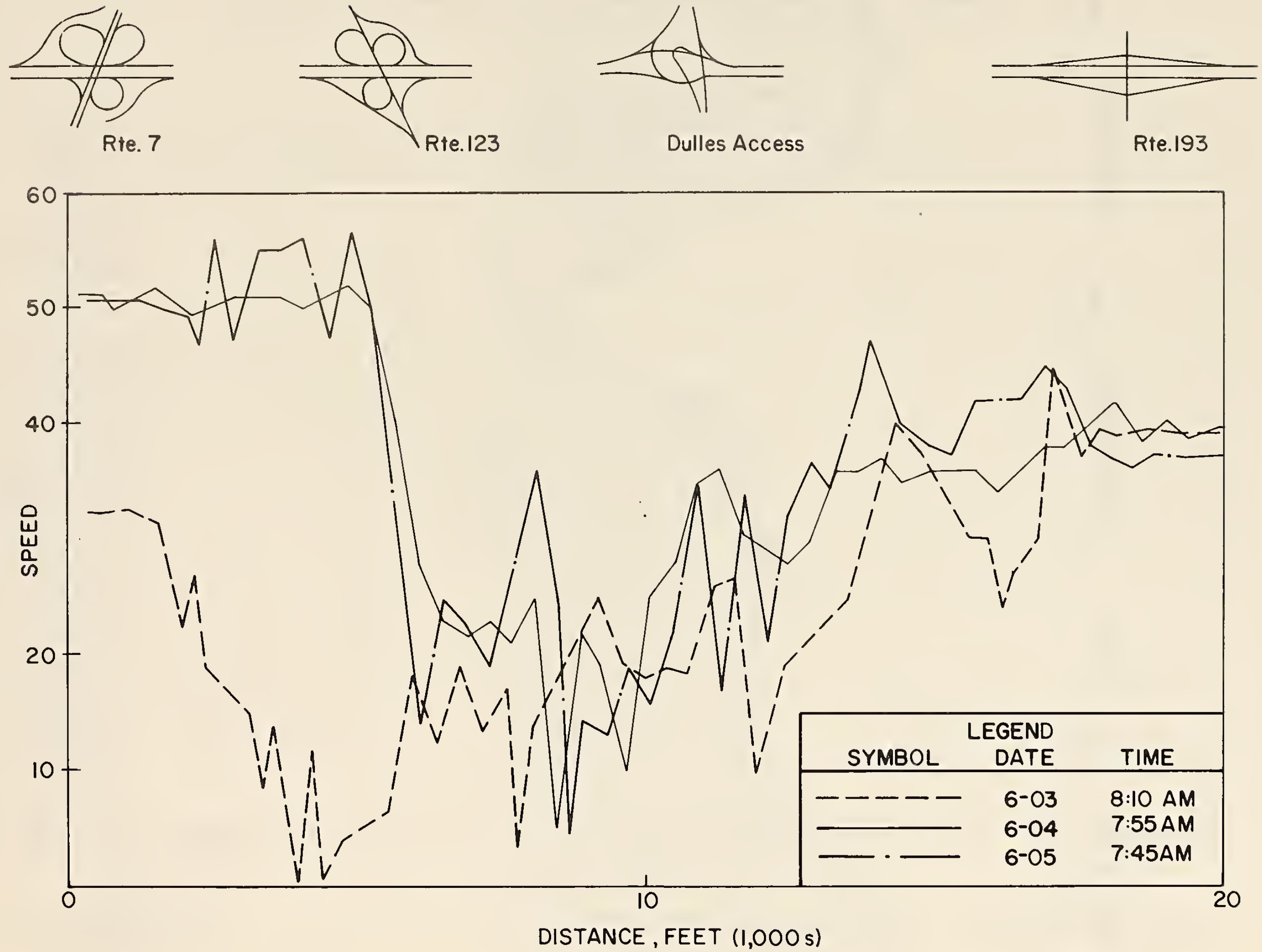


Figure 29. Example of a queue on a four-lane freeway

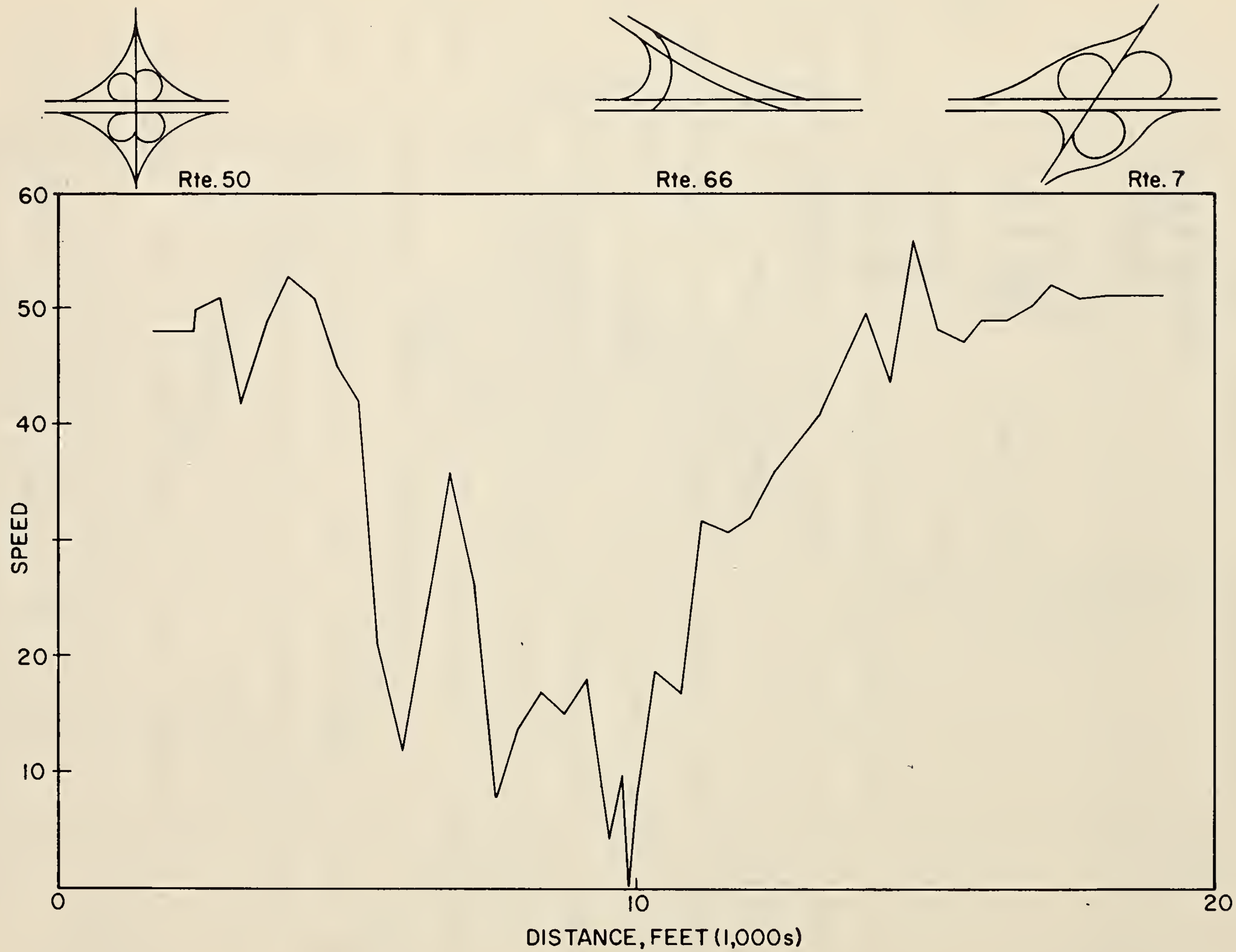


Figure 30. Example of a queue on a four-lane freeway

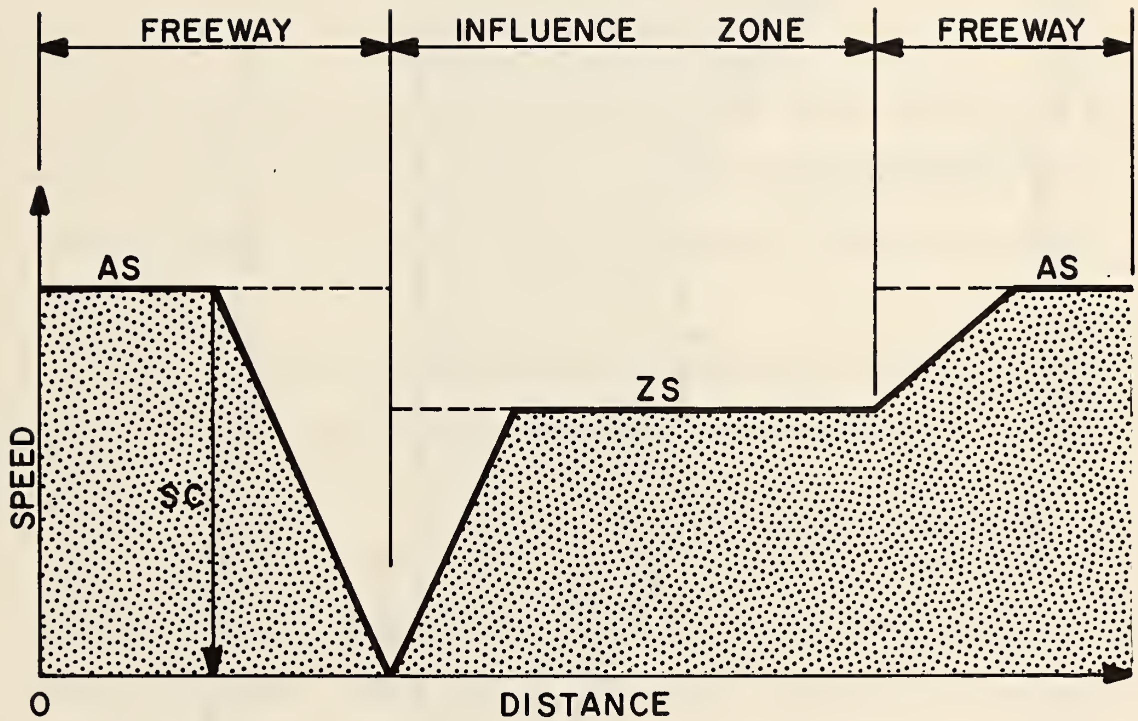


Figure 31. Schematic speed profile of traffic operation through a traffic control zone on the verge of queuing.

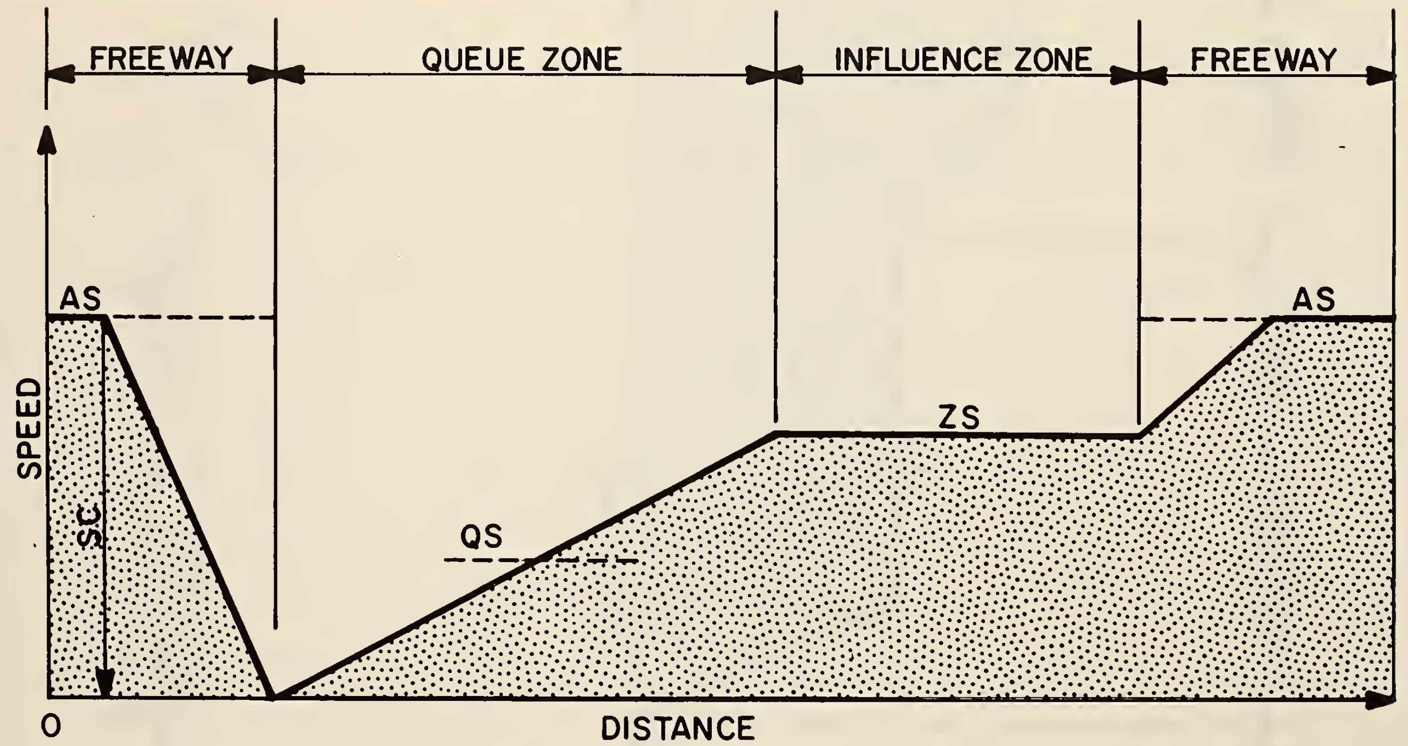


Figure 32. Schematic speed profile of traffic operation through a traffic control zone where a queue has occurred.

CQ = Operation cost for a vehicle going through the queue zone at speed QS

OC = CR + CSC + CQ - CN - CQN

Highway Average Speed

The determination of the speed AS, ZS and QS are critical to the determination of motorist impacts. In addition to the vehicle operation costs, speed has an influence on accidents, value of time and pollution.

Speed curves that showed speed as a function of lane volume were taken from the Highway Capacity Manual[47]. The Volumes and Speeds developed from the field studies were overplotted on the highway capacity based curves for comparison and validation of the basic speed volume relationships. There was tremendous scatter of the speeds at particular volumes around the capacity manual curve, but no reason not to adopt the capacity manual curves.

It was decided to structure an algorithm for inclusion in the computer program developed to generate motorist impacts. The speed algorithm is based on Figure 33

Where

DS = Freeway design speed

C = Capacity of freeway or lane closure in 1000's

SL = Speed limit on freeway or of the lane closure

S1 = 90% of the design speed

S2 = The speed at capacity as determined by the following

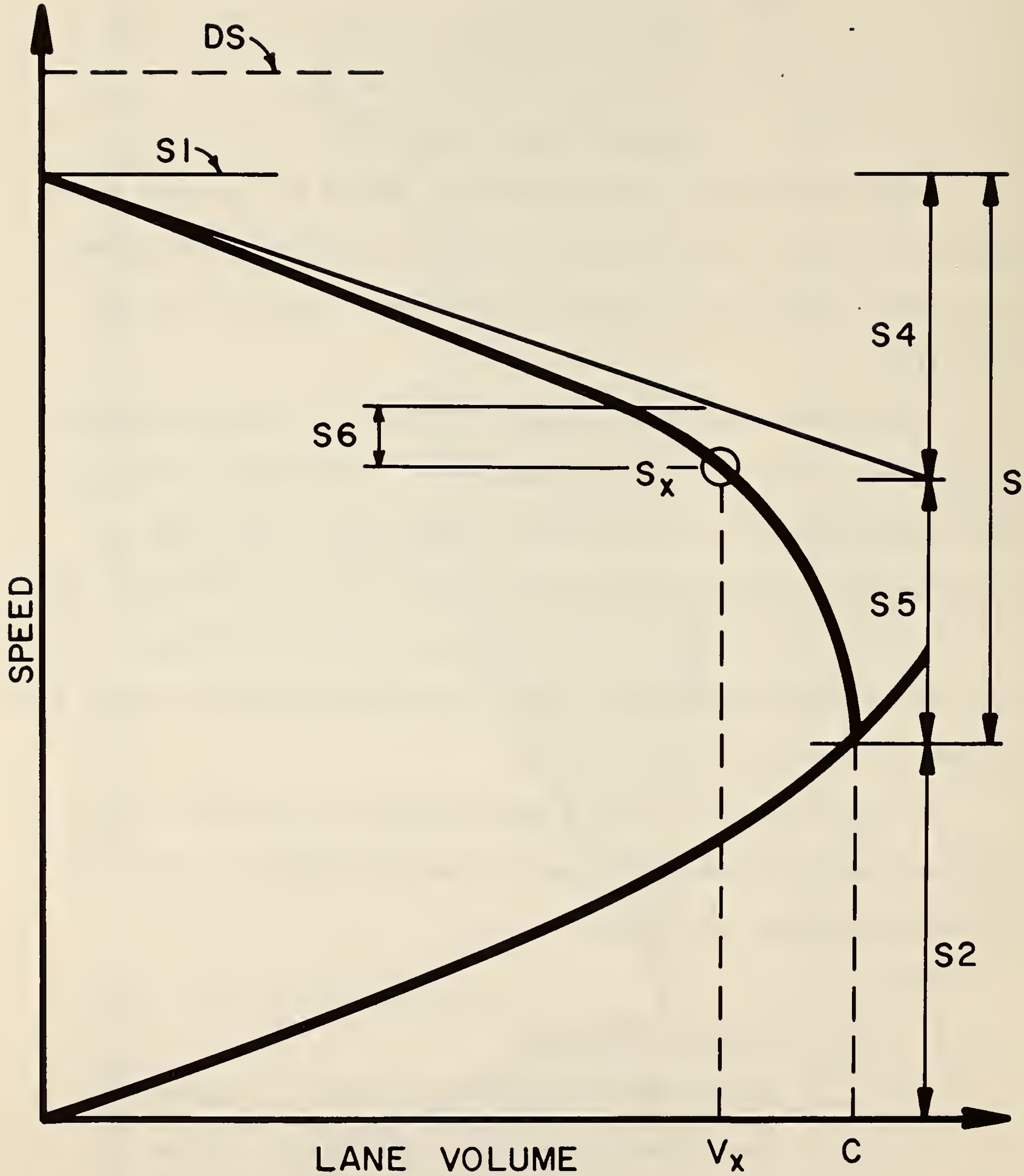


Figure 33. Relationships between design speed and capacity

function $(12C + .5C^{4.46})$

V_x = Any volume in 1000's

S_x = Speed for a given volume-capacity ratio

It involves the following steps:

Step 1 Design Speed Curve

1 $S1 = .9DS$

2 $S2 = 12C + .5C^{4.46}$

3 $S3 = S1 - S2$

4 $S4 = (.4V-10) \times V/C$

5 $S5 = S3 - S4, \geq 0$

6 $S6 = (V/C)^{25} \times S5$

7 $S_d = S1 - S4 - S6$

Step 2 Speed Limit Curve

8 $S_1 = SL \times .9 - 3.6 \times V/C$

Step 3 Select Minimum Speed

9 S_x = Minimum between (S_d or S_1)

Design Speed Curves for 70, 60 and 50 mph were developed following the Step 1 procedure. The resulting speed curves are shown in Figure 34.

The Step 2 computation was made for speed limits of 60, 50, 40 and 30 mph and these are shown plotted with a 70 mph design curve in Figure 35. The program selects the lesser of the speeds determined in the two steps and assigned it to a speed matrix for range of volume capacity ratio values. The speed matrix for an eight-lane freeway is illustrated in Table 15.

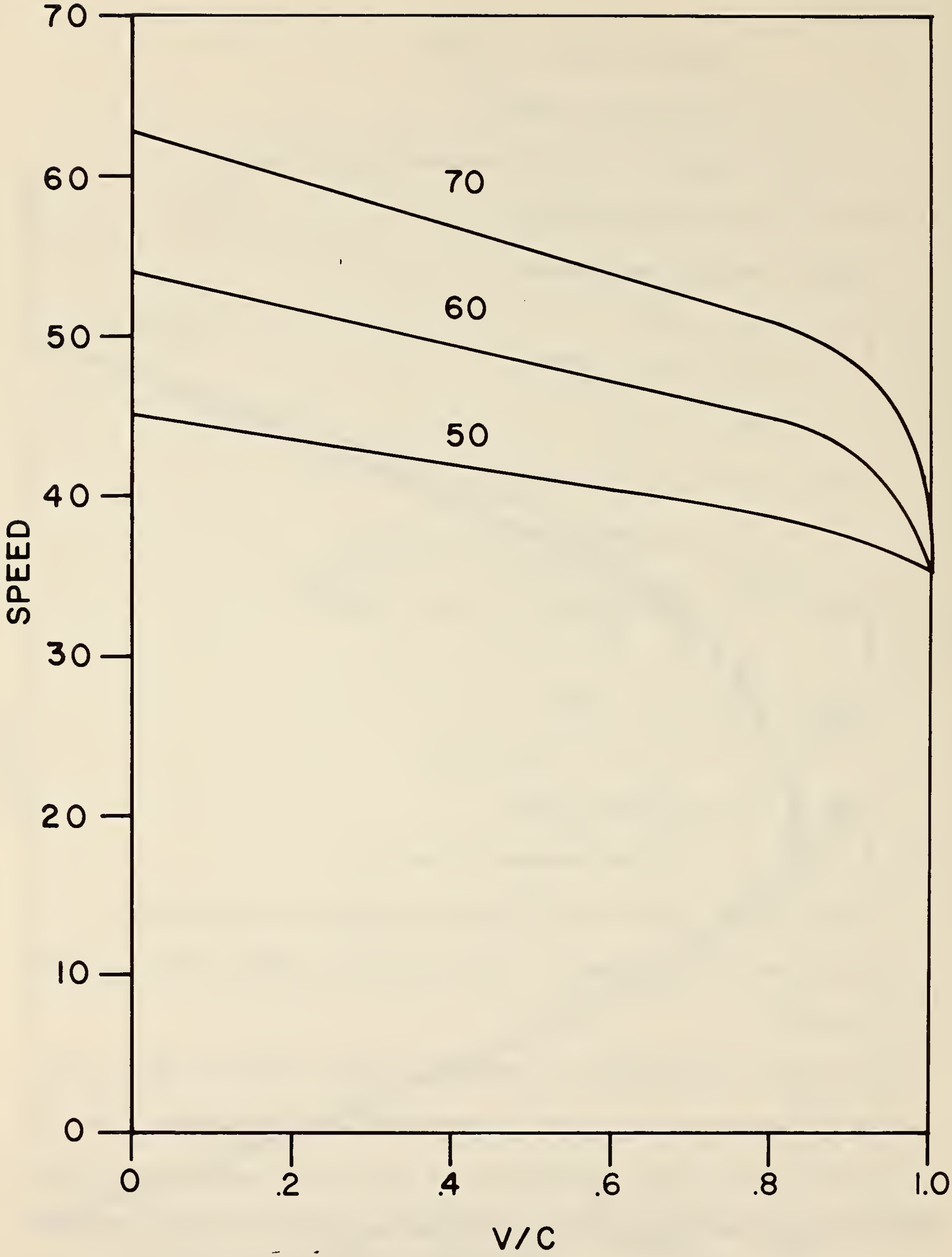


Figure 34. Speed curves for highway designs of 70, 60, and 50 mph where speed limit equals design speed

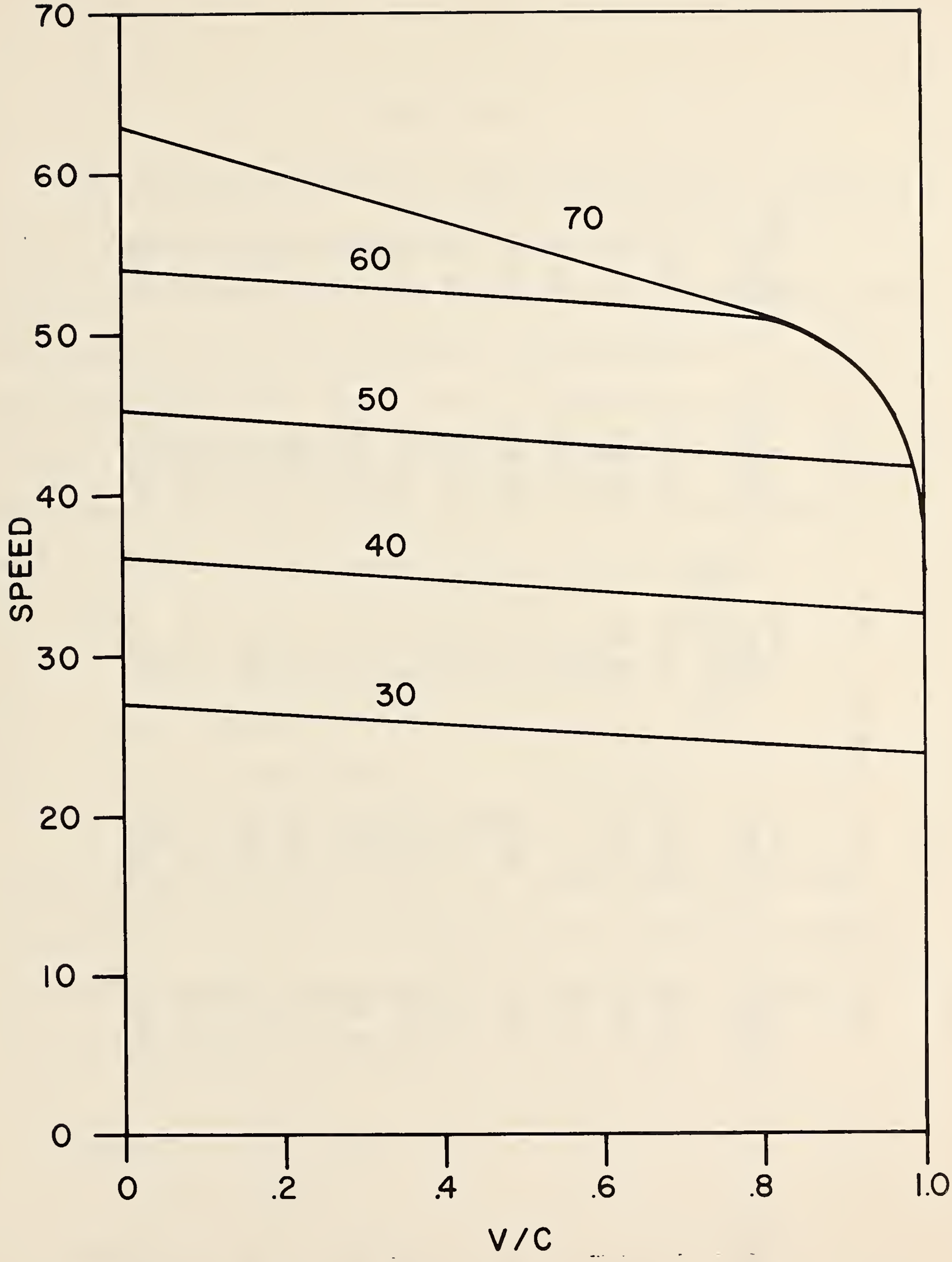


Figure 35. Speed curves for a range of speed limits on a road with a 70 mph design speed

Table 15. Computer generated speed matrix for an eight-lane freeway

V/C Ratio	3 lanes open	2 lanes open	1 lane open	Traffic Detoured	All lanes open
			SPEED (MPH)		
0.0	45.00	45.00	45.00	40.50	54.00
0.10	44.64	44.64	44.64	40.14	53.64
0.20	44.28	44.28	44.28	39.78	53.28
0.30	43.92	43.92	43.92	39.42	52.92
0.40	43.56	43.56	43.56	39.06	52.56
0.50	43.20	43.20	43.20	38.70	52.20
0.60	42.84	42.84	42.84	38.34	51.84
0.70	42.48	42.48	42.48	37.98	51.48
0.80	42.12	42.12	42.12	37.62	51.12
0.90	41.76	41.76	41.76	37.26	50.76
1.00	31.56	31.56	25.73	15.53	35.00

Queue Delay

The assumption is made that a lane closure category can handle up to its capacity without generating a queue. This is the area to the right of the capacity curve shown in Figure 36. As the demand increases, a queue occurs which is shown as the shaded area. At t_2, Y vehicles are being delayed. The vehicle that was added to the queue at t_2 will be delayed time X. The program performs an hourly analysis. The queue delay applicable to all vehicles handled by the influence zone in the hour is based on the relationships illustrated in Figure 37.

Where

CAP = Lane closure capacity in 1000's

Q = Queue in 1000's

T = Time in hours

VOL = Demand volume in 1000's

Of the volume CAP passing through the influence zone in each hour, the delay due to queuing associated with each vehicle is the average delay to all vehicles during the hour. This DELAY is computed as follows for the three hours illustrated:

T.1 = Q.1/VOL.1

DELAY(1) = (0 + T.1)/2

T.2 = Q.2/VOL.2

DELAY(2) = (T.1 + T.2)/2

DELAY(3) = (T.2 + 0)/2

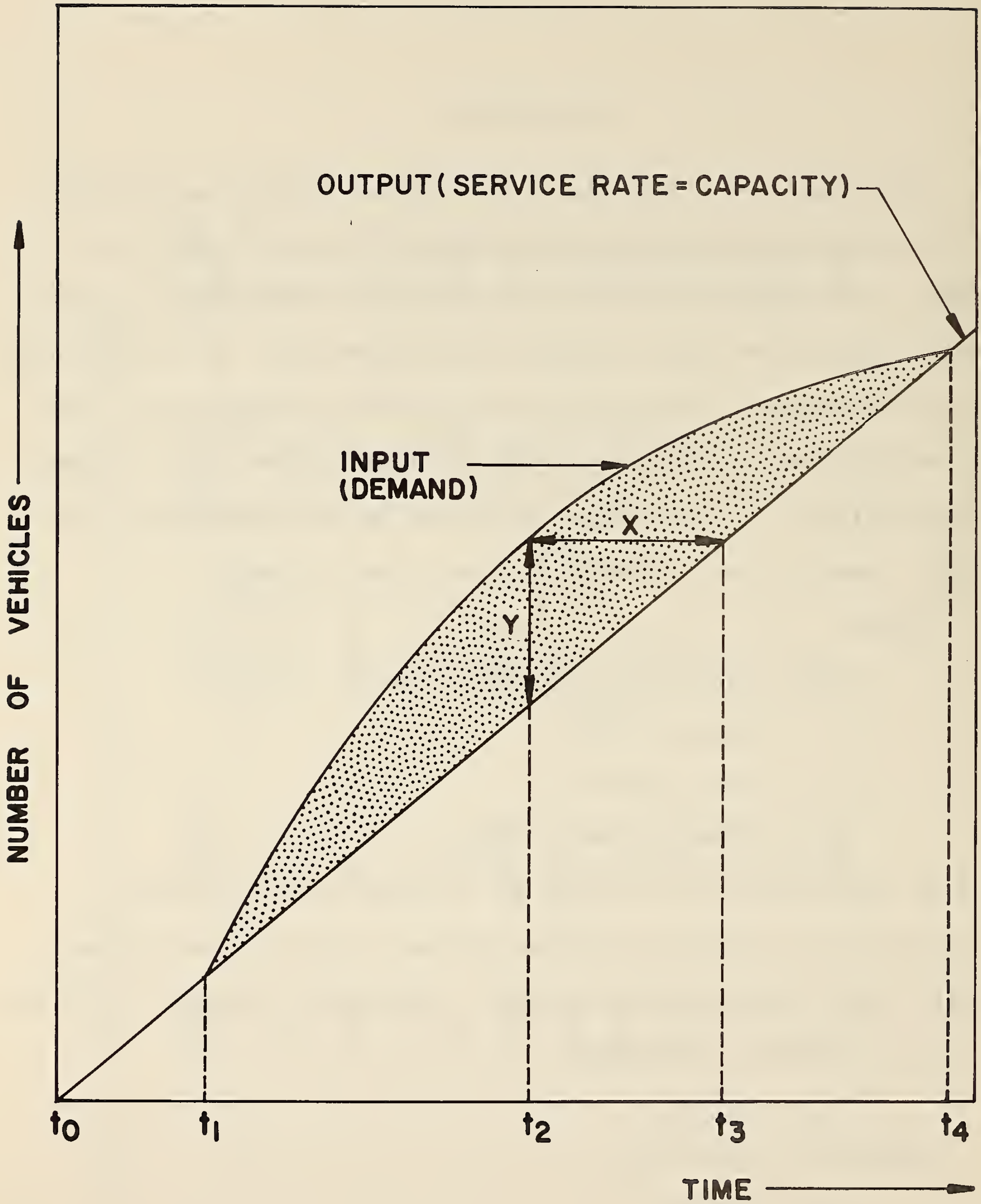


Figure 36. Demand and capacity relationships where a queue is created

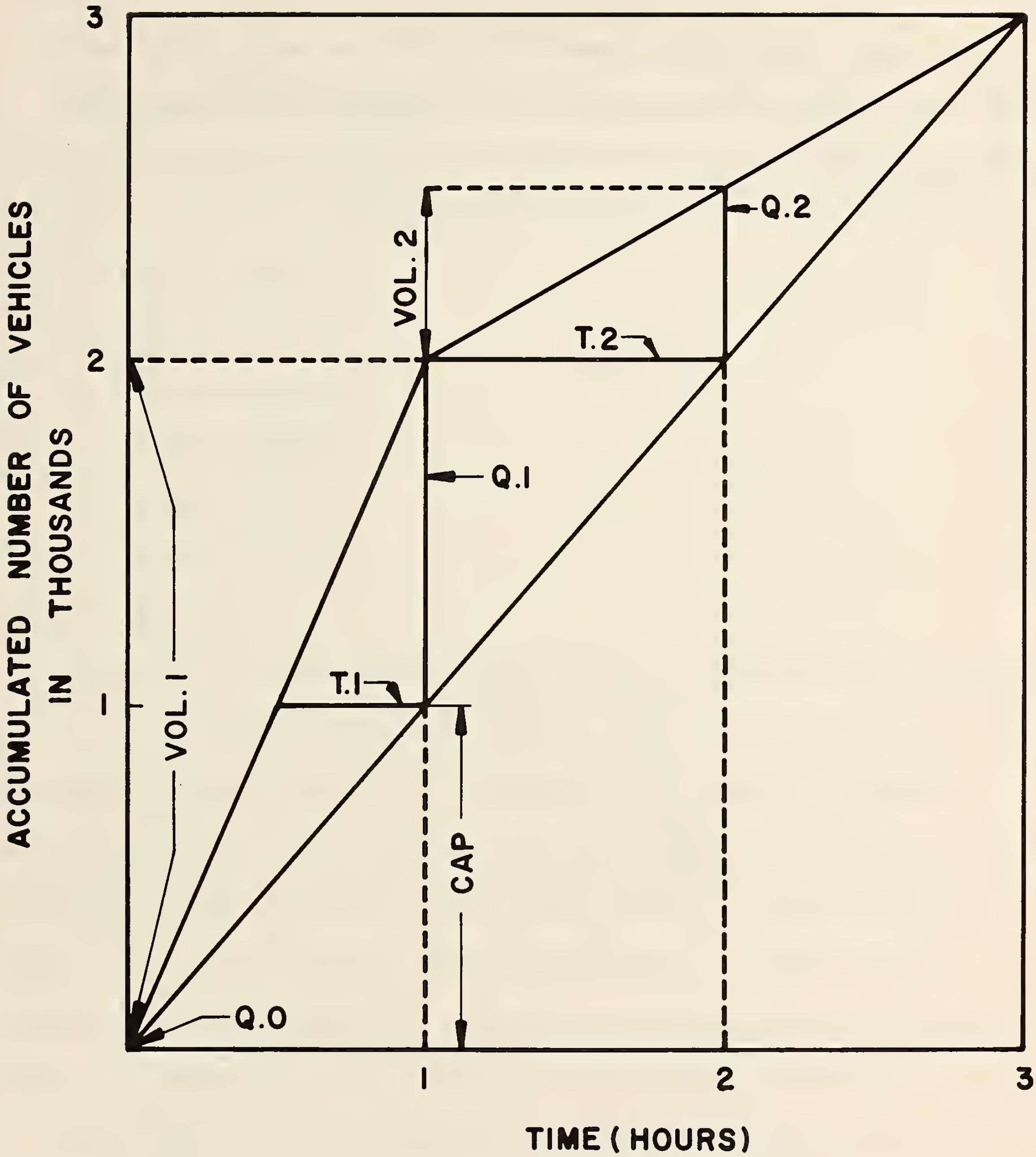


Figure 37. Relationship between queue delay, capacity and demand volume

The queue zone distance shown in Figure 32, on which normal operation cost is based, is the product of the DELAY and the average speed in the queue zone.

Traffic

Distributions

The hourly distribution of all traffic and the distribution of traffic among six trip purposes for each hour of the day is required in the program. The six trip purposes required for the program value of time routine are as follows:

1. Work
2. Social-Recreational
3. Personal Business
4. Vacation
5. School
6. Commercial

The program is supplied with default hourly distributions of traffic for each trip purpose in each direction as shown in Figure 38. The five passenger car trip purpose distributions, based on the consultant's origin and destination survey data, show directional differences for work trips and school trips only. This is the reason for not showing directional distributions for the other trip purposes in Figure 38. The default commercial vehicle distribution is based on data obtained from the U. S. Department of Transportation 1972 Truck Weight Study.

The program user has the option to specify any trip purpose hourly distribution by direction thereby overriding any of the program defaults. The option also is available to balance the distribution of traffic when no directional difference is desired for any of the trip purposes. When specified, this option causes both directional distributions to be averaged and the average distribution assigned to both directions.

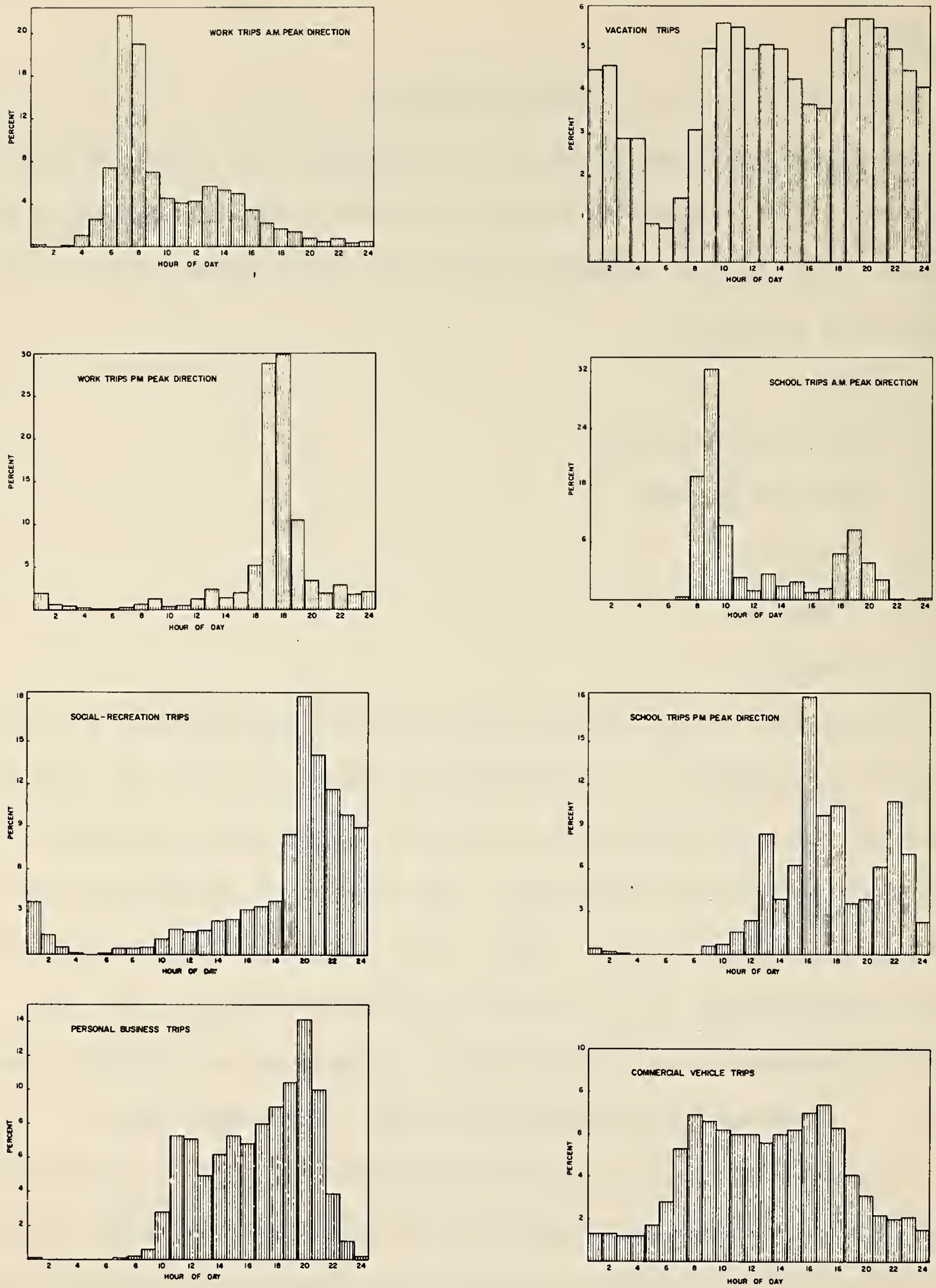


Figure 38. Hourly distributions of traffic by trip purpose and direction developed for use as defaults in program

A single set of trip purpose distributions is used for both directions and for the initial and final year as a program default.

For passenger car trip purposes, the default distribution is based on the 1972 edition of the publication Automobile Facts and Figures. By assuming a commercial percentage of ten percent the following default trip purpose distribution was created:

Work	33.1
Social-Recreational	18.9
Personal Business	28.4
Vacation	0.1
School	9.5
Commercial	10.0

The assumed default value for the commercial vehicles is actually meaningless because it will be replaced by required program input. Nevertheless, it is needed to satisfy data initialization requirements which requires a balanced trip purpose distribution.

The required traffic input to the program includes the specification of an initial and final year commercial percentage of total traffic volume. Whatever else the user might do in terms of specifying changes in other trip purpose percentages, the commercial percentage is fixed and all distribution balancing is forced to reconcile with the specified commercial percentage.

Based on the hourly and trip purpose distributions, the percentage of the daily traffic represented by each trip purpose each hour of the day is established for the initial and final years in both directions.

These percentages are either adjusted to reflect an optional input distribution of all traffic or summed for each hour of the day to create a distribution of all traffic. The hourly distributions of all traffic created from the default distributions are shown in Figures 39 and 40.

Once the hourly distribution of all traffic is established, the percentages of the daily traffic represented by each trip purpose are converted to percentages of the hourly traffic represented by each trip purpose. These initial and final year distributions are converted to base year and yearly increments respectively using a linear interpolation. The base year and yearly increments are used to establish the traffic distribution in each year of the analysis.

Volume

The program requires as input the initial and final year AADT and the initial and final year percentage of AADT in the AM peak direction. A linear interpolation is made between initial and final year to establish the AADT and the percentage of AADT in the AM peak direction for each year of the analysis. Using these and the previously established hourly distribution of traffic, the hourly volumes are computed for each hour of the day.

The detour route normal hourly volumes are also computed from the detour route AADT assuming the same distribution of all traffic and percentage of AADT in the AM peak direction. The default detour route AADT is 20,000 which may be overridden with input.

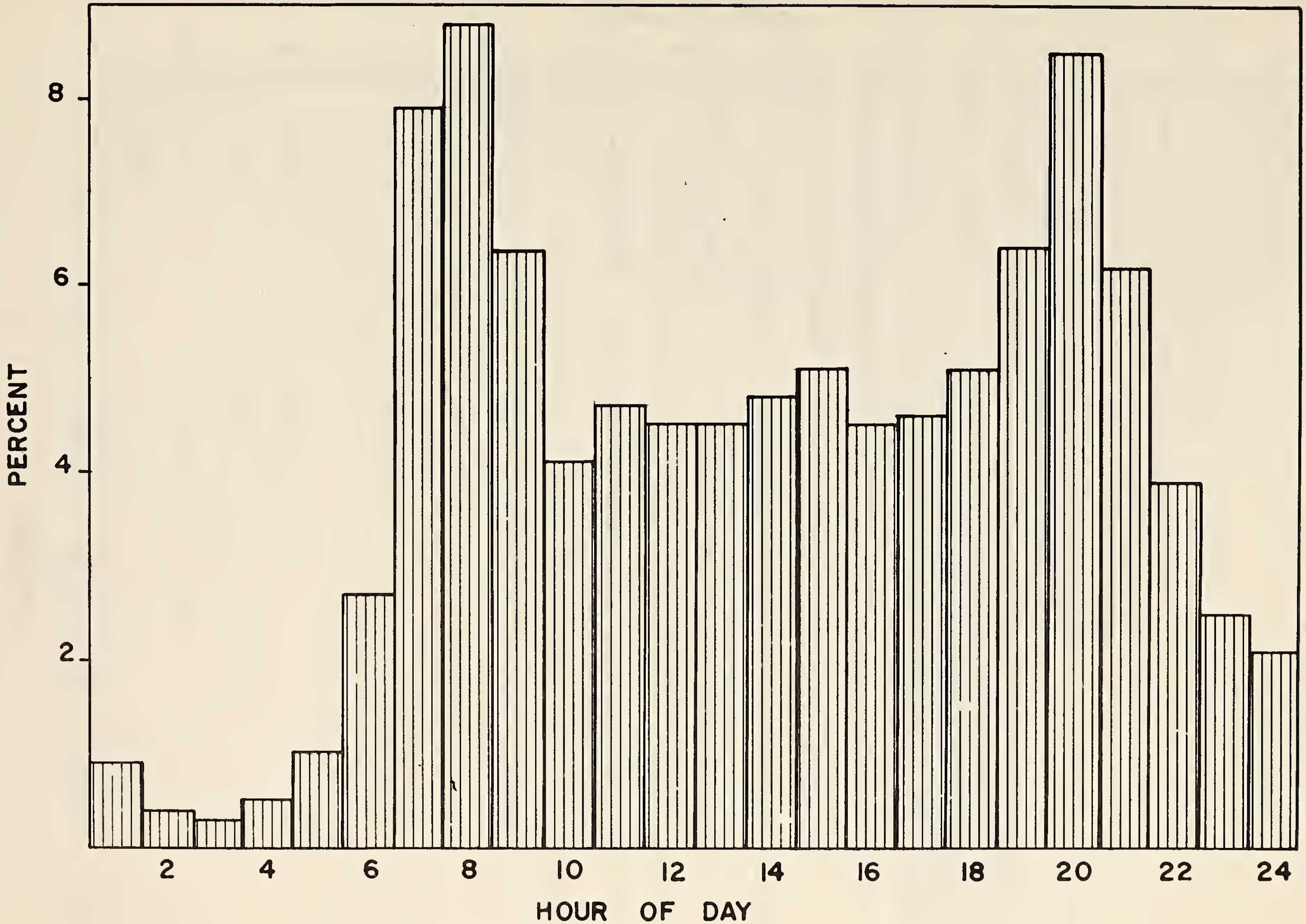


Figure 39. Distribution of "All Traffic" in the AM peak direction

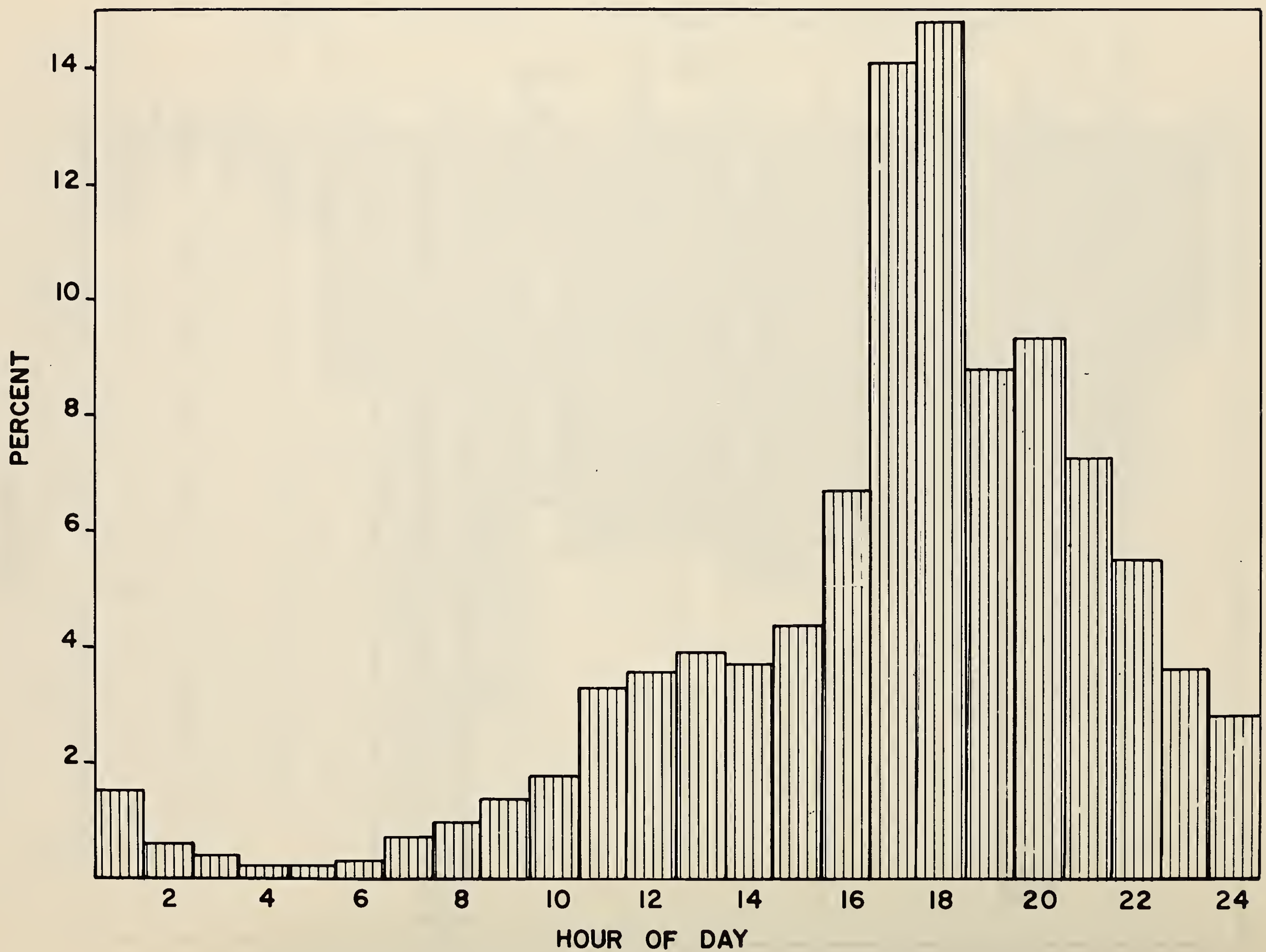


Figure 40. Distribution of "All Traffic" in the PM peak direction

Vehicle Parameters

The weight and cost of an average passenger car and of a composite commercial vehicle are required by the program to compute increased operating costs.

The program computes the commercial vehicle cost and weight from the distribution of commercial vehicles, the average weight of each vehicle, and the average cost of a vehicle within that class. The default weights assumed by the program are taken from the U.S. Department of Transportation 1972 Truck Weight Study and are shown in Table 16.

The default average purchase costs of commercial vehicles are presented in NCHRP 33. These were updated using the cost trends shown in Figure 41. Program default values for vehicle weight and base purchase price for a passenger car-light truck composite and three classes of heavy trucks follows:

FHWA Classification	Description	Weight in kips	Costs in Dollars
Passenger Car		4.2	$ 3,000
200000	Pickup Truck		
210000	Heavy, 2-axle 4-tire truck		
220000	2-axle 6-tire truck	15.38	7,300
322000	4-axle semi truck(2S2)	39.76	24,400
332000	5-axle semi truck(3S2)	53.55	39,300

Table 16. Summary of truck data developed from computer printout developed by FHWA from the U.S. 1972 Truck Weight Study

Description of Sample Location	*FHWA Truck Classification 200000	210000	220000	322000	332000
	Gross Weight in Kips				
1. Calif. Sta. 001					
Volume Percentage	10.09	0.89	1.76	0.23	0.42
Mean Weighted	6.80	--	13.24	29.92	48.02
2. Conn. Sta. 009					
Volume Percentage	3.36	0.68	2.97	4.46	4.81
Mean Weighted	6.75	7.49	17.68	44.19	57.84
3. Hawaii Sta. 012					
Volume Percentage	8.52	0.89	1.77	0.30	0.40
Mean Weighted	5.61	7.58	15.68	51.07	69.39
4. Idaho Sta. 028					
Volume Percentage	20.20	0.16	2.91	0.20	1.37
Mean Weighted	--	--	12.88	34.67	50.00
5. Mass. Sta. 002					
Volume Percentage	3.94	0.83	3.71	4.88	4.01
Mean Weighted	4.84	6.20	14.97	36.84	46.36
6. Mass. Sta. 006					
Volume Percentage	4.02	0.41	2.71	2.71	3.11
Mean Weighted	5.22	6.81	14.99	39.46	44.79
7. Mass. Sta. 012					
Volume Percentage	4.56	0.73	3.16	2.14	2.09
Mean Weighted	5.08	8.14	15.05	35.70	50.77
8. New Jersey Sta. 058					
Volume Percentage	3.47	1.02	2.76	2.94	7.25
Mean Weighted	6.69	8.49	17.49	44.14	60.52
9. New Jersey Sta. 060					
Volume Percentage	3.09	0.68	4.03	2.35	2.70
Mean Weighted	7.40	8.79	17.23	46.29	60.91
10. New Hamp. Sta. 012					
Volume Percentage	9.50	0.34	3.03	1.85	2.19
Mean Weighted	5.45	7.18	14.64	35.32	46.86
Summary of 10 Locations					
Volume Percentage	7.1	.67	2.9	2.2	2.8
Mean Weighted	5.98	7.58	15.38	39.76	53.55

*See Page 117

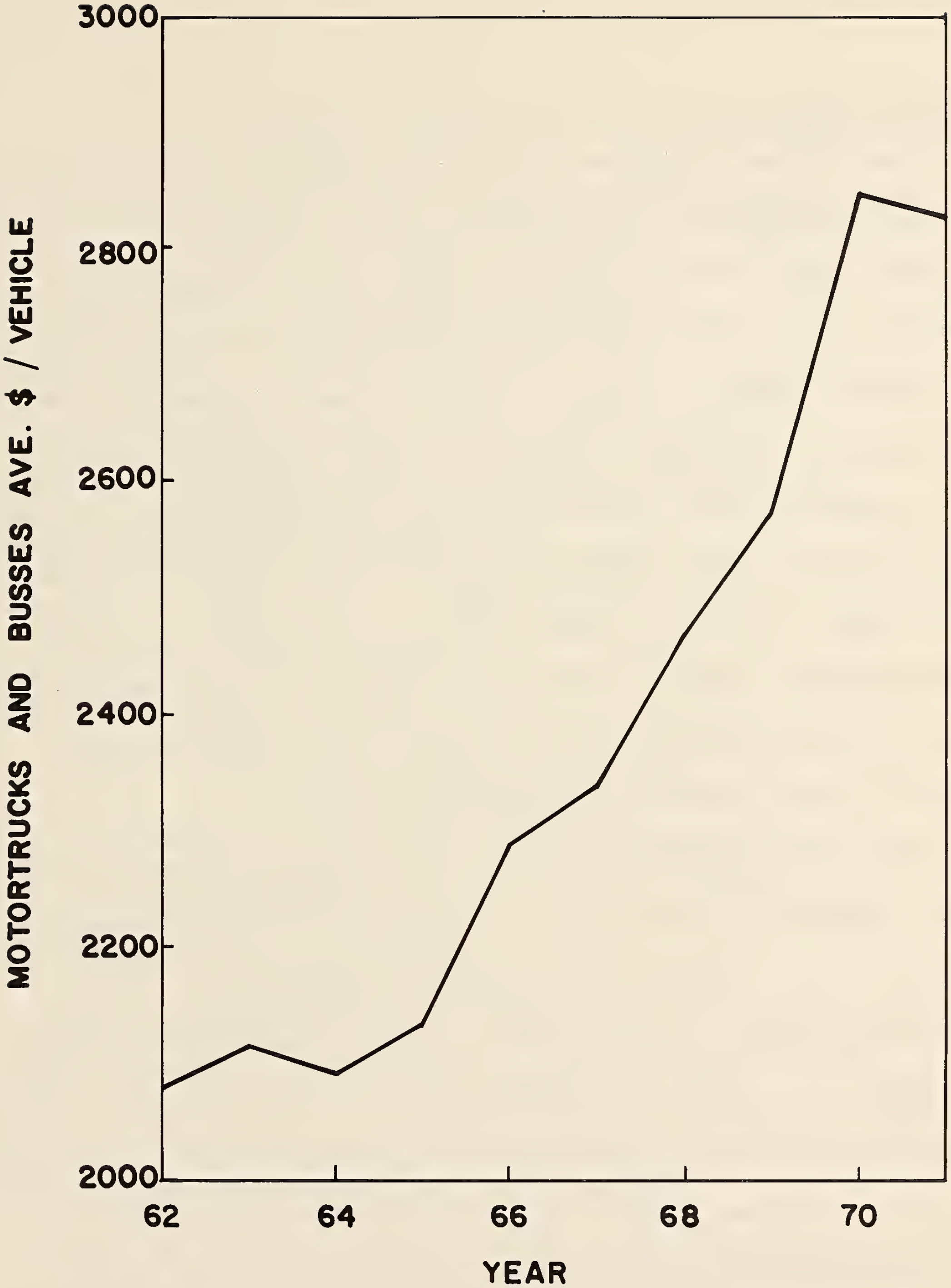


Figure 41. Price trend of commercial vehicles over a ten-year period (1972 Automobile Facts and Figures, Motor Vehicle Manufacturers Association)

Operation Costs

In many economic analyses, tables and graphs are developed to permit a rapid computation of the operating costs associated with a range of vehicle speeds. These tables and graphs quickly become outdated as the unit price of the basic vehicle consumption parameters change.

For this economic analysis, a series of basic consumption models were developed. Included are models for fuel consumption, tire wear, oil consumption, vehicle maintenance costs and depreciation. The models define changes in the consumption parameters due to roadway alignment, vehicle weight and running speed. The actual consumption parameter relationships may change in the future. However, they are not expected to vary as much as the unit costs which have been subject to rapid changes in recent years due to the energy shortage.

The models developed for each of the consumption parameters draw on data presently reported in the literature[48-53]. The consumption parameters fuel, tires, oil, maintenance and depreciation are each addressed separately. A relationship is established between consumption, speed and a range of alignment values for a base vehicle. Then consumption rates for a range of vehicles, based on weight, are related to the basic alignment model. Next, the relationships between consumption, speed and speed changes are determined for a base vehicle. Again, the consumption rates for a range of vehicles are examined and a relationship developed to expand the basic model to fit any vehicle weight category.

Fuel Consumption Models for Vertical Alignment

Both Winfrey and Claffey have developed tables and graphs reflecting gasoline consumption in gallons per mile for a range of plus and minus grades.[48-52] Data from both sources were converted to gallons per hour and replotted. The basic relationships for a standard passenger vehicle were examined and found similar from both sources. For passenger vehicles, Winfrey made extensive use of early Claffey data. Therefore, it was decided to develop grade models using basic Claffey information. In NCHRP 13[51] a graph (Figure 5, page 13) is presented by Claffey showing actual increases of fuel consumption in gallons per hour for different grades at different speeds. An attempt was made to develop models for both positive and negative grades using this data. However, the effect of free rolling vehicles on negative grades could not be adequately accommodated so the use of this information was limited to developing positive grade models.

The data presented by Claffey is for an 8-cylinder 1964 sedan with automatic transmission weighing 4175 pounds when loaded. The consumption rate in gallons per hour for both positive and negative grades is plotted for three speed curves (20, 30 and 50 mph).

A model was developed for each of the three speed curves using a regression analysis to fit the following general model:

$$\mathrm{Ln}Y = A + BX$$

To smooth the models and generalize them for the computer program module, both the intercept value A and the regression coefficient B were modeled as a function of speed. The resulting set of curves closely duplicated the curve sets presented by Winfrey and Claffey for positive grades. The regression statistics for the three curves and coefficient models are shown in Table 17.

The model set used to predict fuel consumption for positive grades is:

F_{vp} = Fuel consumption in gallons per vehicle per hour

A_p = Intercept constant for positive grade fuel model

B_p = Regression coefficient for positive grade fuel model

S = Speed in miles per hour

G_p = Positive grade in percent

$$A_p = -.45 + .0214S$$

$$B_p = .0348 + .0214 \ln S$$

$$F_{vp} = e^{(A_p + B_p \times G_p)}$$

For the negative grades it was not possible to develop a set of equations which adequately predicted fuel consumption because two different conditions exist. A vehicle can be moved by gravity alone or by some combination of gravity and throttle. From source data developed by Claffey and available to this study through Winfrey, fuel consumption rates in gallons per hour for vehicles operating at speeds below floating were shown to fall below the idling rate. Floating operation is the maximum speed achieved on a negative grade without throttle. This reduced fuel consumption rate is caused by the increasing air fuel ratio which develops as speed increases while the carburetor operates

Table 17. Regression statistics for vertical alignment fuel consumption models for passenger cars

Speed	A	B	SE(B)	t	r	SE(est)	FValue
20 mph	.0687	.09710	.018	5.4	.952	.211	29
30 mph	.402	.111	.012	8.9	.970	.146	80
50 mph	.940	.117	.008	14.7	.993	.093	216

in the idle system range. A curve was fit to data developed by Claffey in NCHRP study 2-5[56] to predict the fuel consumption rate for speeds below floating speed on negative grades. The model of this curve is:

$$F_f = 1/(1.61 + .1(S))$$

where

F_f = Fuel consumption in gallons per vehicle per hour

S = Speed (MPH)

A model was developed to predict floating speed by negative grade based on a graph published by Winfrey[50]. The model is as follows:

S_f = Float speed in mph

G_n = Negative grade in percent

$$S_f = 3 - 7G_n$$

The assumption is made that fuel consumption rates on negative grades follow the below float model until float speed is reached. Once the float speed is reached, the rate of fuel consumption for any increase in speed is equal to the rate increase on a normal tangent section for the same speed increment, i.e., the consumption curve parallels the normal tangent section fuel consumption curve. The use of the set of models for vertical alignment is graphically illustrated in Figure 42.

Fuel Consumption Models for Horizontal Alignment

Winfrey [48] found very little published information available on the influence of horizontal curves on fuel consumption. Consequently, his approach was to compute the horsepower developed on curves at

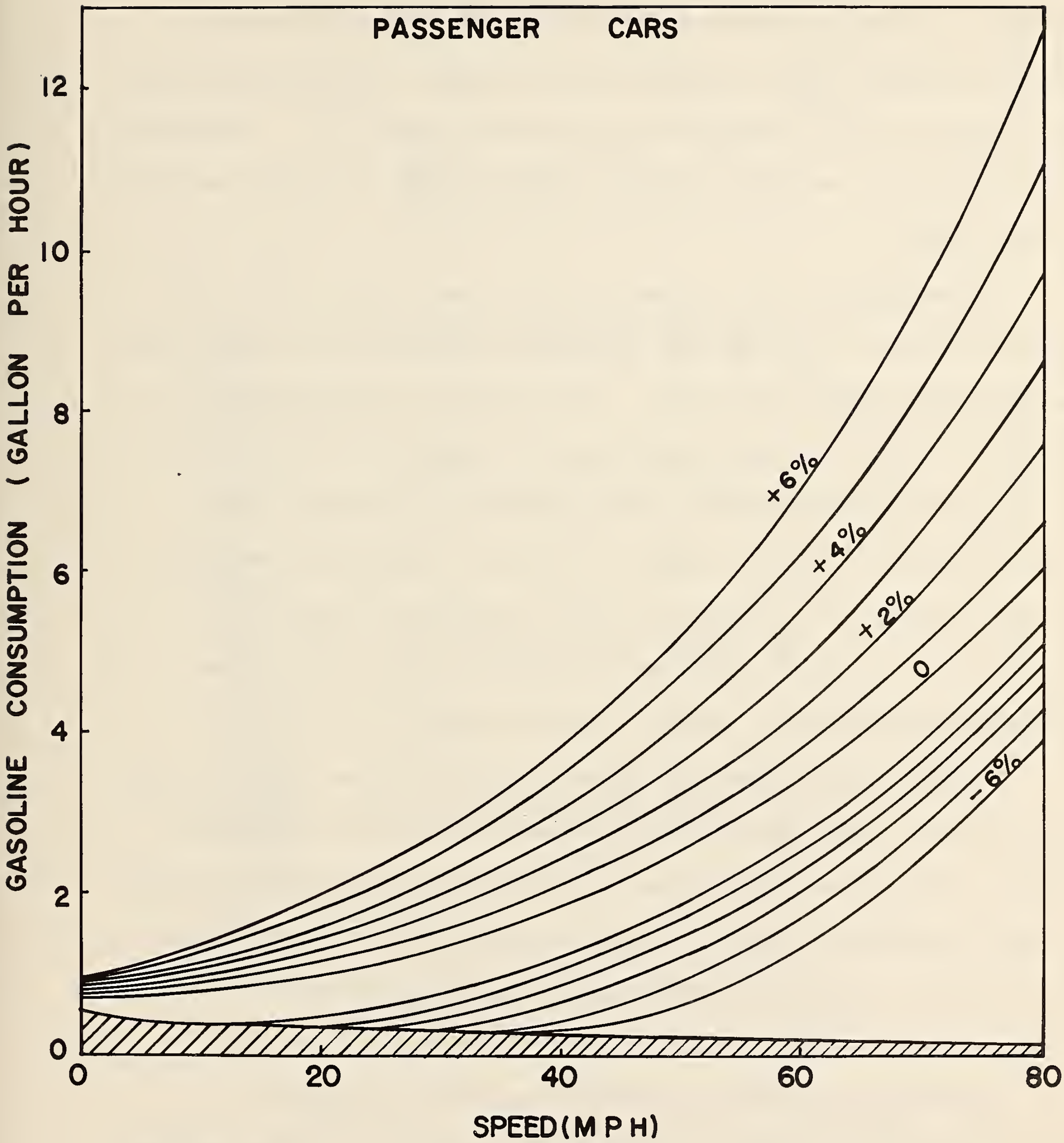


Figure 42. Vertical alignment gasoline consumption curves for basic passenger car

different speeds and then base fuel consumption on comparable horsepower developed on level tangents and plus grades. Claffey made actual measurements of fuel consumption on different curves[49-50]. Therefore, the Claffey data was used to develop models of fuel consumption on horizontal curves.

The speed-grade-fuel consumption models were based on data developed by Claffey for a 8-cylinder 1964 sedan with automatic transmission weighing 4175 pounds when loaded. The horizontal curve data shown by Claffey for this same vehicle were used as a basis for the horizontal curve-speed models developed for the operating cost module. These curves were for a 4400 lb. weight. Therefore, the weight correction factor established by Claffey was used to convert the curves to be applicable to a 4175 lb. vehicle. The factor is 8% change in fuel consumption per 1000 lbs. change in vehicle weight.

Claffey's graphs were blown up and fuel consumption rates, in gallons per mile, were scaled off of his chart for 10 mph increments of speed. For each horizontal curve the gallons per mile values were converted to gallons per hour. A model was developed for each horizontal curve using a regression analysis to fit the following general model:

$$\ln Y = A + BX$$

The models and analysis statistics are shown in Table 18.

To smooth the models and generalize them for the computer program, both the A intercepts and B coefficients were modeled so that they could be determined for any horizontal degree of curvature.

Table 18. Regression statistics for horizontal alignment fuel consumption models for passenger cars

Horizontal Curvature	A	B	SE(B)	t	v	SE(est)	Fvalue
2 degree	- .554	.0313	.001	31.9	.998	.052	1017
4 degree	- .607	.0341	.001	31.1	.997	.058	970
6 degree	- .606	.0354	.002	18.2	.996	.061	332
8 degree	- .665	.0400	.002	19.3	.996	.066	372
10 degree	- .671	.0437	.002	21.8	.998	.045	474
12 degree	- .728	.0498	.002	28.3	.999	.039	801
90 degree	-1.071	.0925	.000	0.1	1.000	.000	.4 Note (2 observations)

A plot of the A intercepts against horizontal curvature suggested two alternate model forms which were:

$$Y = A + B\ln X$$

$$LnY = A + B\ln X$$

Additionally, the range of curvatures expected for the freeways being considered was not expected to exceed 6 degrees. Therefore, the data for the 90 degree curve was deleted in one set of analyses to determine if a better fitting model could be developed. Finally, data was included for zero degree curvature and weighted to force the resulting model to predict the coefficients established for the level, tangent model. The models and analysis statistics are shown in Table 19.

A plot of the B regression coefficient suggested that a curve of the form LnY = A + BX would provide the best fit if the 90 degree curve was not used. Again the zero degree curvature was added to the data matrix and weighted to force a fit to the curve defining the speed-fuel consumption relationship for level tangent sections. The results of this analysis also are shown in Table 19.

Because there was no model for the B coefficient which included the 90 degree curve, both models 1 and 3 were not considered further. Both models 2 and 4 were considered and tables developed to compare the two. Both were deficient in predicting fuel consumption values which exceed the zero degree curvature base value. Based on Claffey's curves all fuel consumption values were the same at 10 mph and at the zero curvature level. Therefore, the predicted values for each curve were factored by the ratio of the fuel consumption rate at zero curvature to

Table 19. Regression statistics for horizontal alignment fuel consumption model coefficients for passenger cars

	Model	A	B	SE(B)	t	r	SE(est)	F Value
1.	2^{o}-90^{o} Curvature Y = A+BlnX	-.463	-.115	.009	-12.3	-.969	.044	152
2.	2^{o}-12^{o} Curvature Y = A+BlnX	-.483	-.087	.005	-18.36	-.987	.016	337
3.	2^{o}-90^{o} Curvature LnY = A+BlnX	-.736	.167	.007	23.9	.991	.033	572
4.	2^{o}-12^{o} Curvature LnY = A+BlnX	-.724	.151	.007	21.3	.990	.023	454
	Regression Coef. B_h LnY = A+BX	-3.562	.0440	.002	28.5	.994	.022	809

the predicted value at 10 mph. Following this factoring, both models 2 and 4 produced the same values. Therefore, model number 2, the simpler of the two being examined, was selected for use in the module.

The fuel consumption model set for horizontal curves is as follows:

F_{pc} = Fuel consumption in gallons per vehicle per hour for passenger cars

S = Speed (MPH)

A = Intercept fuel model constant

B = Model regression coefficient

D = The horizontal curvature between zero and twelve degrees

$$A_h = -.483 - .087 \mathrm{Ln} D$$

$$B_h = e^{-3.562 + .044D}$$

$$Y = e^{(A_h + B_h S)}$$

The predicted values are shown in Table 20 and plotted in Figure 43.

Alignment Weight Factor

For the purpose of converting the basic passenger car model set to any vehicle weight class, Winfrey's level tangents table data for fuel consumption for 5-, 12-, 40-, and 50-kip commercial vehicles was divided by comparable 4-kip passenger car data. This produces a ratio for the range of speeds shown in Table 21. An examination of the ratio values revealed a trend reversal at both the high and low speed ends. Models were developed for 6 speeds examining the following equation forms:

$$Y = A + B \mathrm{Ln} X$$

$$\mathrm{Ln} Y = A + B \mathrm{Ln} X$$

Table 20. Passenger car gasoline consumption in gallons per hour per vehicle.

Degree Curve	Speed(mph)						
	10	20	30	40	50	60	70
2	.819	1.116	1.521	2.073	2.826	3.851	5.249
4	.819	1.148	1.610	2.258	3.167	4.441	6.227
6	.819	1.185	1.714	2.479	3.586	5.188	7.505
8	.819	1.226	1.834	2.745	4.108	6.148	9.201
10	.819	1.272	1.976	3.068	4.765	7.401	xxxxx
12	.819	1.325	2.142	3.465	5.603	9.062	xxxxx
14	.819	1.384	2.340	3.956	6.687	xxxxx	xxxxx

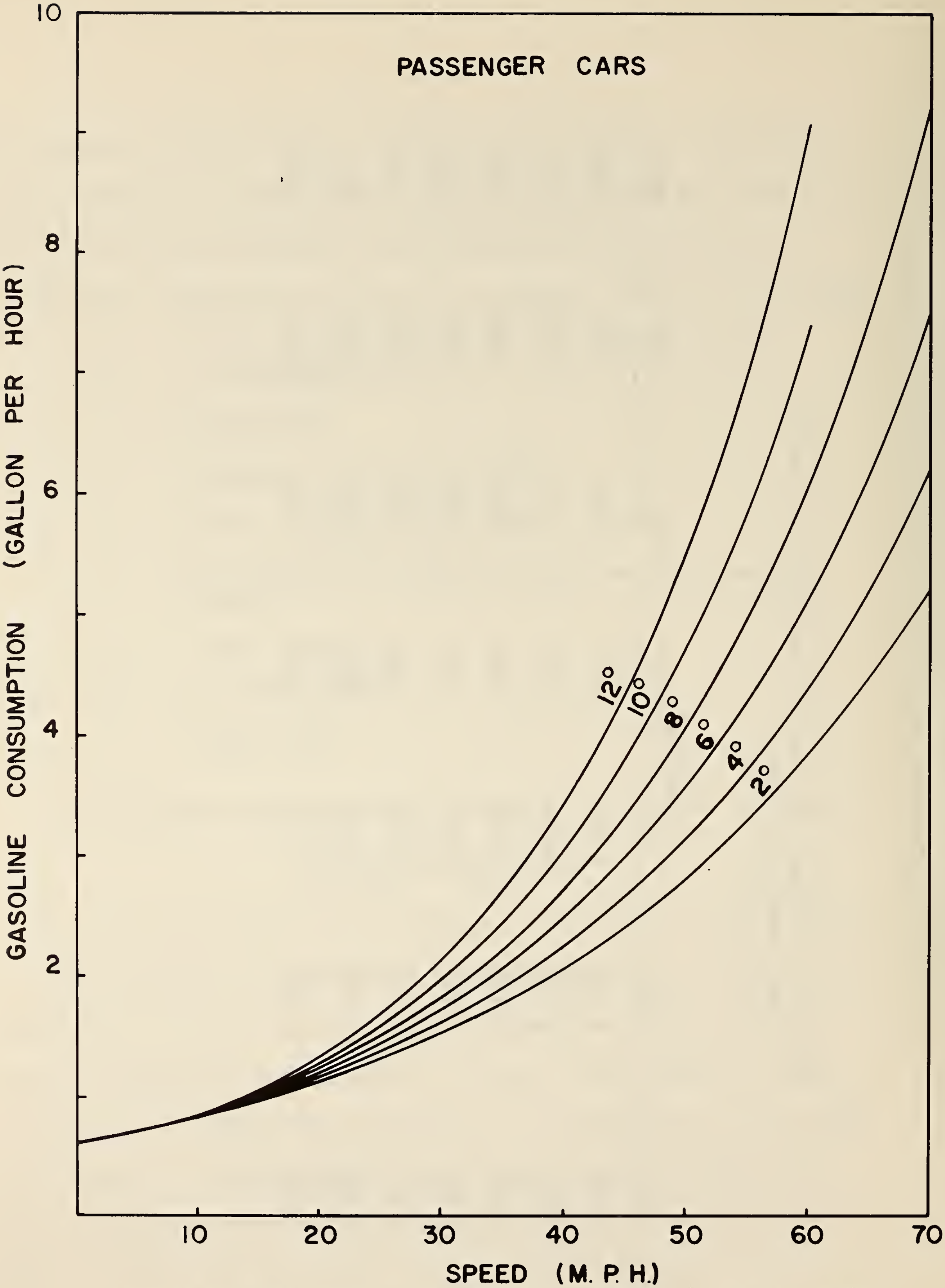


Figure 43. Gasoline Consumption Curves for horizontal curves in 2 degree increments for basic passenger car

Table 21. Ratio of gasoline consumption per vehicle hour to passenger car consumption for a range of vehicle weights on level target sections.

Speed	Weight in kips on normal tangent sections					Ratio			
	4	5	12	40	50				
mph	Gasoline Consumption					5/4	12/4	40/4	50/4
10	.633	.666	1.273	4.127	2.128	1.05	2.01	6.52	3.36
20	.918	.972	1.976	4.424	2.481	1.06	2.15	4.82	2.70
30	1.283	1.392	2.796	5.018	3.120	1.08	2.18	3.91	2.43
40	1.788	2.013	3.816	6.244	4.265	1.13	2.13	3.49	2.39
50	2.480	3.016	5.200	8.805	6.416	1.22	2.09	3.55	2.59
60	3.457	4.825	7.308	14.850	9.911	1.40	2.11	4.29	2.87
70	4.900	8.464				1.73			
80	7.057								

The statistics for the resulting weight ratio models are shown in Table 22. The A and B coefficients were plotted and were revealed to be polynominals. A polynominal regression was made to fit each of the coefficients and the statistics shown in Table 23. The final weight ratio model for converting passenger car fuel consumption is as follows:

A_r = Weight Ratio Model Intercept

B_r = Weight Ratio Model Regression Coefficient

R_w = Weight Ratio Factor for Fuel

W = Weight in kips

S = Speed (MPH)

$$A_r = 1/(.46 + .0344S = .00031S^2)$$

$$B_r = 1/(.78 + .0437S - .00047S^2)$$

$$R_w = e^{(-A_r + B_r LnW)}$$

Speed Changes

Both the Winfrey[48,50] and Claffey[49,51] tables on excess gallons of gasoline consumed were reviewed to check their similarity. Winfrey's excess consumption levels were twice those of Claffey for the highest speed levels (50-70 mph) though they were very similar at the lower levels. Winfrey's tables seemed to be based on Sawhill's data[53] which covered only heavy trucks and only the lower speed levels. In examining the Winfrey and Claffey data in relation to the Sawhill data, the differences were much more nominal. Therefore, because Claffey had developed actual field data for passenger vehicles, his data was relied upon to develop a set of curves for passenger cars.

Table 22. Regression statistics for weight ratio models for passenger car gasoline consumption on tangent sections.

Speed & Model	A	B	SE(B)	t	r	SE(est)	F Value
10 LnY = A+BlnS	-1.248	.8304	.066	13	.994	.119	160
20 LnY = A+Bln	-1.014	.7036	.031	23	.998	.055	528
30 LnY = A+BlnX	- .846	.6113	.051	12	.993	.092	143
40 LnY = A+BlnX	- .733	.5520	.054	10	.991	.097	106
50 LnY = A+BlnX	- .692	.5522	.043	13	.994	.078	157
60 LnY = A+BlnX	- .729	.5948	.057	11	.991	.102	111

Table 23. Regression statistics for the A_r and B_r coefficients in the weight ratio model set for gasoline consumption

Model	A	B	C	SE(Est)	F Value
A_r $Y = 1/(A+B+CX^2)$	.460	.0344	-.00031	.047	72
B_r $Y = 1/(A+B+CX^2)$	.780	.0437	-.00047	.055	47

The data presented by Claffey was presented in two tables (NCHRP 111, Tables 7 and 8)[52] and represented the excess gallons of gasoline consumed per stop-go and slowdown speed change cycle for a composite passenger vehicle. The excess gasoline consumed for each increment of speed change was plotted and except for the stop value was a straight line. Winfrey's data suggested that the curves should be convex in shape and continuous through the stop speed change value. Therefore, models were developed for the 70 mph and 40 mph curves using a regression analysis to fit the model, $Y_c = A + BLnX$, and the analysis statistics for the regression models are shown in Table 24.

The two curves fit the Claffey data quite closely and from the plots the relationship between the different speed curves seem approximately constant. Therefore, it was assumed that a linear interpretation between the A and B coefficients at the 70 and 40 mph levels would adequately permit the prediction of the appropriate coefficients for any operating speed. The following model which is plotted in Figure 44 resulted from this assumption:

S = Speed in mph

SC = Speed change in mph

F_{sc} = Excess gallons of gasoline consumed per speed change cycle

$$A_{sc} = -8 + .0035S$$

$$B_{sc} = .91 + .00134S$$

$$F_{sc} = e^{(A_{sc} + B_{sc} LnSC)}$$

Table 24. Regression statistics for speed change models for passenger car excess gasoline consumption per cycle

Initial Speed & Model	A	B	SE(B)	t	r	SE(est)	F Value
40 Y = A+BlnX	-7.884	.960	.031	31	.998	.074	969
70 Y = A+BlnX	-7.798	1.001	.044	23	.994	.137	524

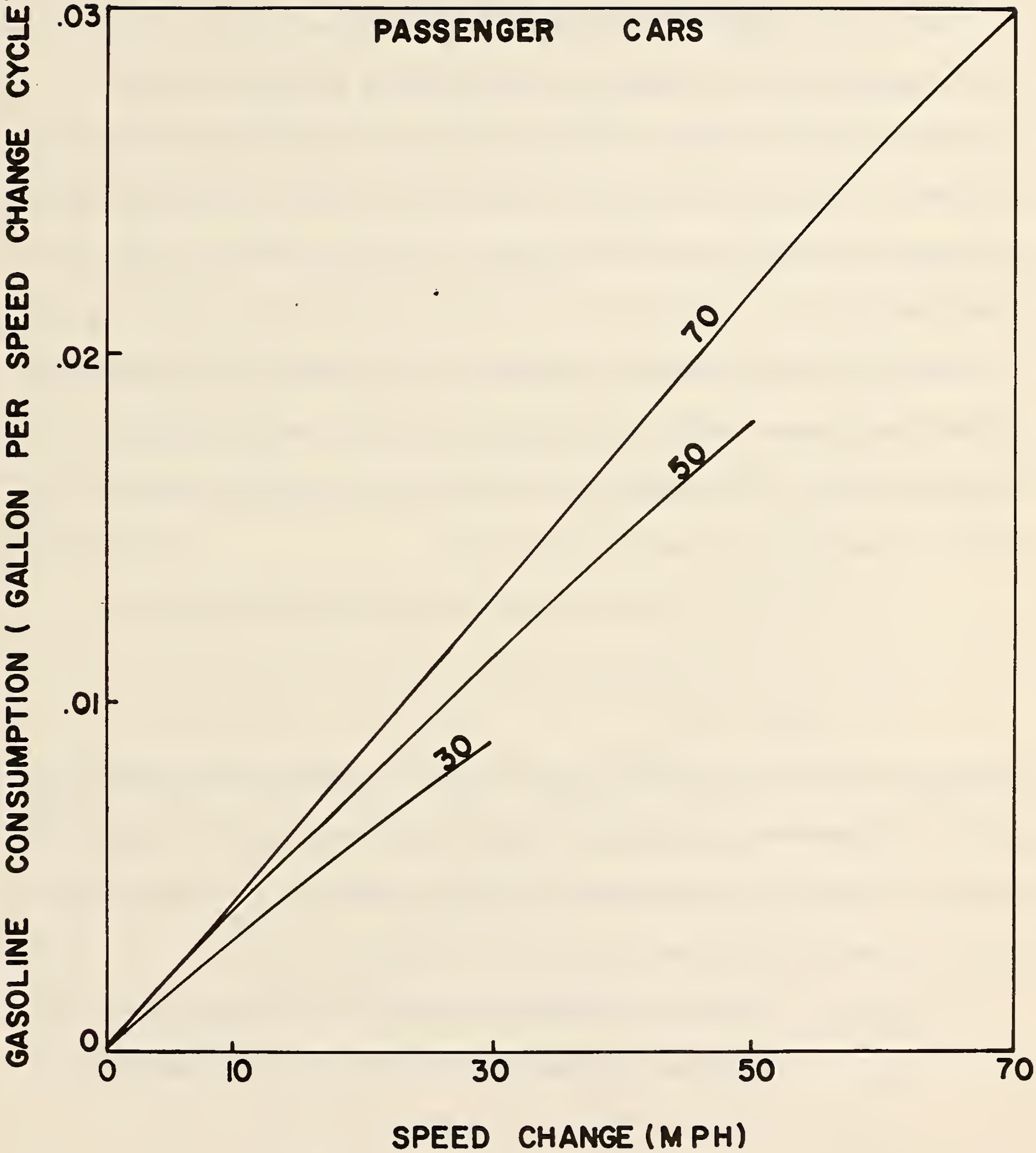


Figure 44. Excess gasoline consumption for speed reductions for a series of initial speed curves for basic passenger car

Speed Change Weight Factor

The curves presented by Sawhill[53] were a smooth set. The model relationship determined above for the composite passenger vehicle was plotted with the Sawhill curves and seemed to fit his series. Therefore, it was determined that the basic passenger car model could be factored to create reasonable excess consumption levels for any weight vehicle.

Sawhill's fuel savings by constant-speed operation at 40 mph were plotted against each weight vehicle and a smooth curve developed to fit these points. The modeled curve follows and treats savings as excess consumption per speed change cycle:

G = Gallons of gasoline consumed per speed change cycle

W = Weight of vehicle in kips

$G = .0015 \times W^{1.2}$

The factor required to convert the base value passenger vehicle excess gallons prediction to a value representative of the vehicle weight class being considered is computed for the 40 mph condition as follows and applies to any initial speed level:

G_{Base} = Gasoline consumption excess for a 4000 lb. vehicle

G_W = Gasoline consumption excess for a W lb. vehicle

$G_{Base} = .0015 \times 4^{1.2}$

$G_W = .0015 \times W^{1.2}$

$R_W = G_W/G_{Base}$

R_W = Weight ratio factor to convert passenger car to any vehicle weight

Alignment Models for Tire Wear

The source curves used for the set of the tire wear models was developed from Winfrey's cost tables.[48] His dollars of tire wear were first converted to .001 inches of tire wear using his indicated unit cost by vehicle class for .001 inches of wear. For the vertical and horizontal alignment curve set, the tire wear data was then converted from 1000 vehicle miles by speed to hourly time wear per hour per vehicle by speed. After plotting sets of curves for horizontal and vertical alignment, three model forms were selected for analysis. These were:

1. $\ln Y = A + BX$
2. $1/Y = A + BX$
3. $\ln Y = A + B\ln X$

The model form and statistics for the best fitting models are shown in Table 25 for three grades and three horizontal curvatures. The grade coefficients were plotted and it was determined that different linear models for positive and negative grades would produce a satisfactory set of models for the vertical alignment curve set. The resulting curve set which is plotted in Figure 45 is as follows:

G_p = Positive grade in percent

G_n = Negative grade in percent

A_p = Positive grade model intercept)) A_v

A_n = Negative grade model intercept)

Table 25. Regression statistics for Horizontal and Vertical Alignment models for passenger car tire wear and the Horizontal Alignment set intercept A_h

Model Tire Wear (.001) inches	A	B	SE(B)	t	r	SE(est)	F Value
0% Grade LnY = A+BlnX	-8.26	2.23	.041	55	.999	.099	3016
8% Grade LnY = A+BlnX	-7.49	2.11	.046	46	.999	.112	2141
-4% Grade LnY = A+BlnX	-7.38	1.96	.045	44	.998	.110	1917
2^o Curve LnY = A+BX	-2.64	0.082	.006	13	.983	.383	176
4% Curve LnY = A+BX	-2.26	0.086	.006	14	.985	.388	189
6% Curve LnY = A+BX	-2.09	0.091	.007	13	.983	.431	172
A_h Y = A+BlnX	0.90	0.590	.036	16	.993	.054	268

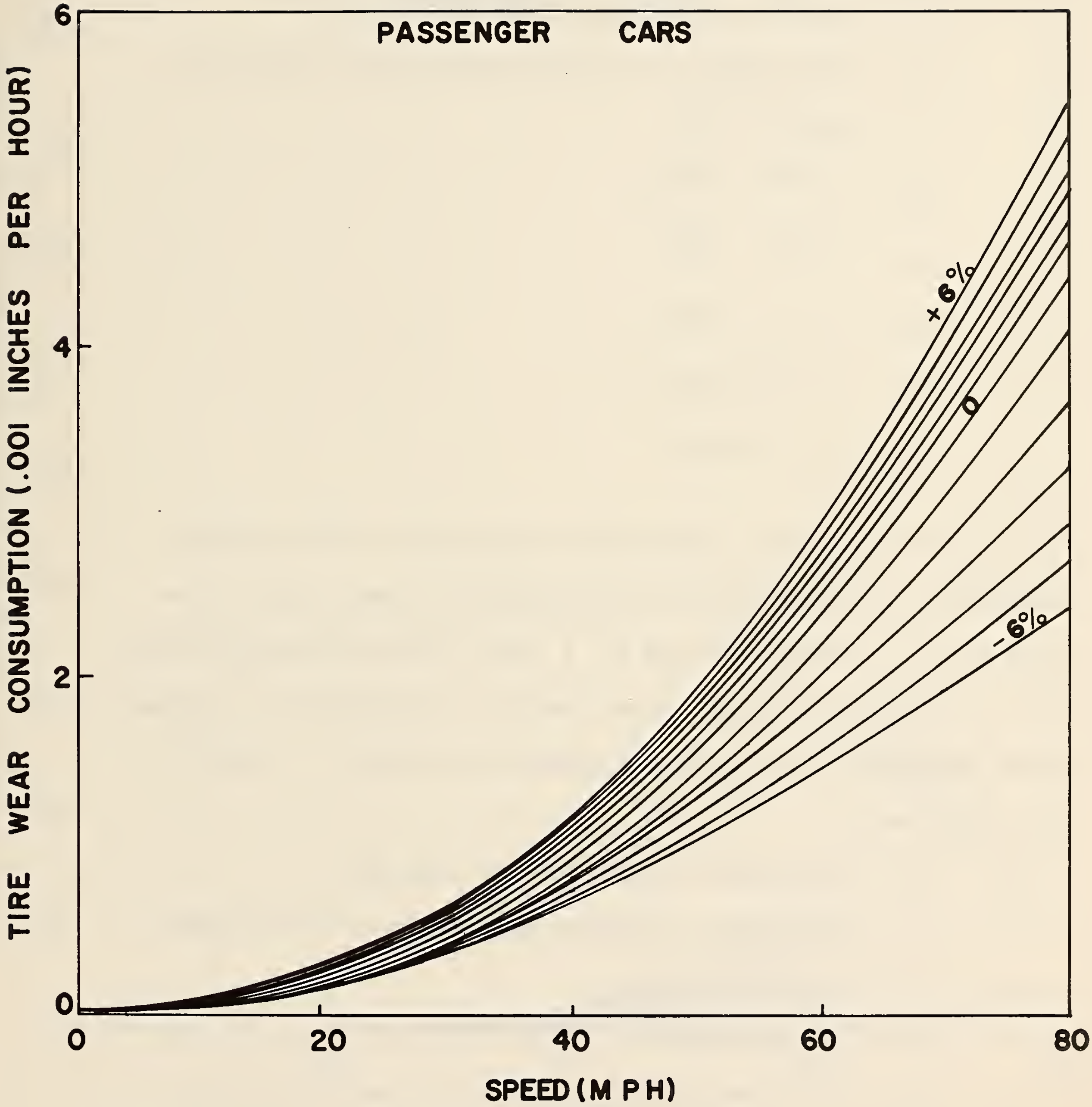


Figure 45. Vertical alignment tire wear curves for basic passenger car

B_p = Positive grade regression coefficient)
) B_v
B_n = Negative grade regression coefficient)

T_v = .001 inches of tire wear per PC vehicle per hour

S = Speed in MPH

$A_p = -8.26 + .095G_p$

$A_n = -8.26 - .20G_n$

$B_p = 2.23 - .015G_p$

$B_n = 2.23 + .070\ G_n$

$T_v = e^{(A_v + B_v LnS)}$

A plot of the horizontal coefficients revealed that the regression coefficient was linear while the intercept value was a curve. The curve was fit to the model form Y = A + BLnX and the resulting statistics are shown in Table 25. The final set of passenger car tire wear models developed for horizontal alignment are plotted in Figure 46 are as follows:

A_h = Horizontal alignment model intercept

B_h = Horizontal alignment model regression coefficient

D = Degree curvature

S = Speed in mph

T_h = .001 inches of tire wear per PC vehicle per hour

$A_h = -3.1 + .59LnD$

$B_h = .077 + .0023D$

$T_h = e^{(A_n + B_n S)}$

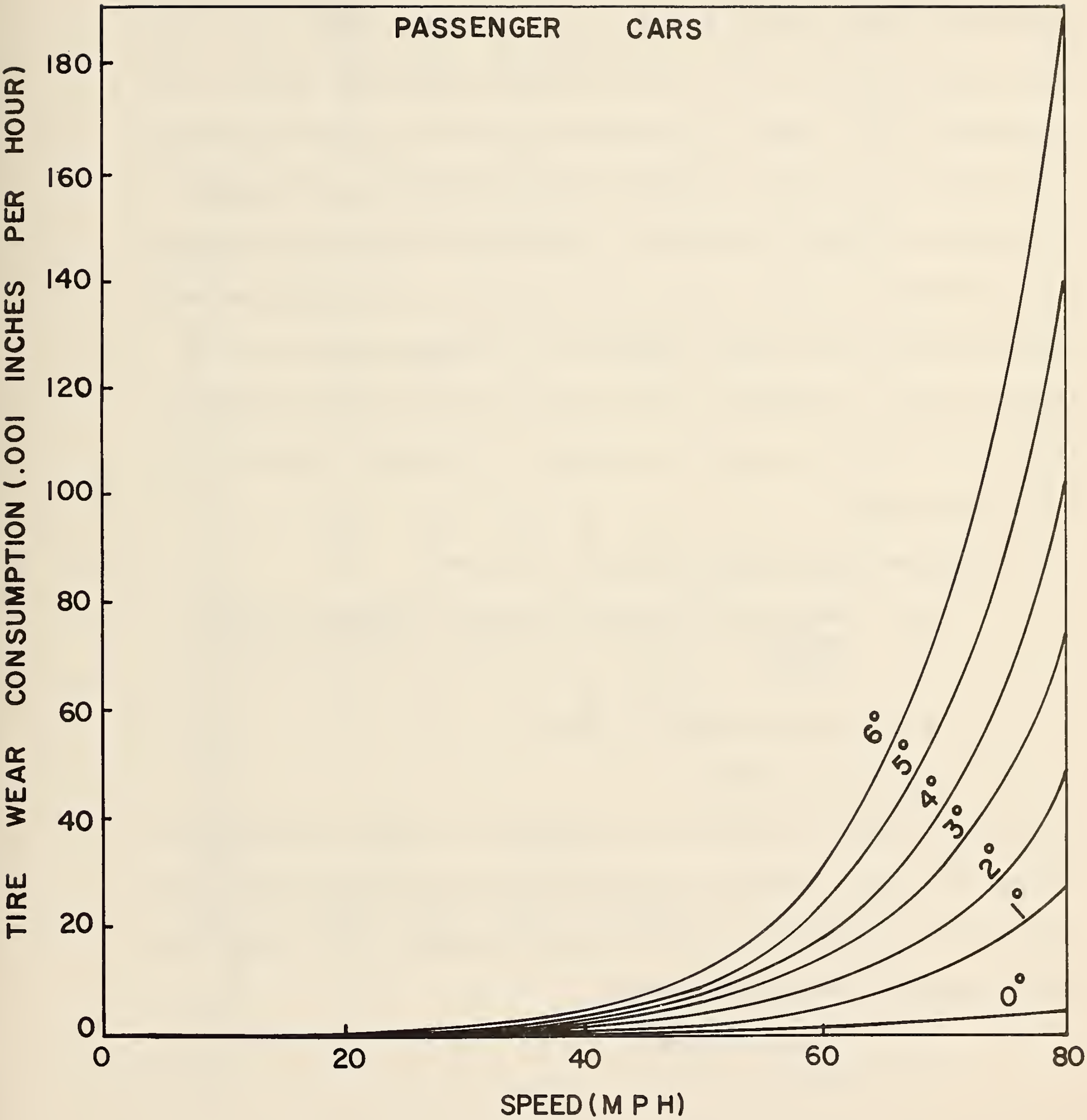


Figure 46. Horizontal alignment tire wear curves for basic passenger car

For the purpose of converting the basic passenger car model set to any vehicle weight class, Winfrey's level tangents table data for the tire wear costs for 5-, 12-, 40-, and 50-kip commercial vehicles was converted to .001 inches of tire wear per hour per vehicle by weight and then fit to the model form LnY = A + BLnX. The resulting model statistics are shown in Table 26. Expanding the models and dividing the resulting tire wear values by the passenger car values produced the tire wear ratios shown in Table 27. A linear curve was fit to the ratio data to determine a model which could be used to produce a factor with which to convert a passenger car tire wear value to any weight tire wear.

The linear model determined was as follows:

R_w = Weight ratio factor to convert passenger car tire wear for alignment to tire wear for any vehicle weight

W = Vehicle weight in kips

$$R_w = .76 + .061W$$

This weight ratio is applied to a passenger car model set based on a weight of 4 kips. Therefore, to generalize the alignment models the factor must be applied to the tire wear produced by the PC model set. This results in the following models:

$$T_v = R_w e^{(A_v + B_v LnS)}$$

$$T_h = R_w e^{(A_h + B_h S)}$$

Table 26. Regression statistics for level tangent section models for a range of vehicle weights for tire wear

Tire Wear (.001) inches	A	B	SE(B)	t	r	SE(est)	F Value
5 kip LnY = A+BlnX	-8.068	2.177	.032	69	.999	.071	4710
12 kip LnY = A+BlnX	-7.584	2.179	.031	70	.999	.070	4832
40 kip LnY = A+BlnX	-7.192	2.242	.055	41	.998	.123	1647
50 kip LnY = A+BlnX	-6.879	2.233	.057	40	.998	.126	1562

Table 27. Model predicted tire wear by vehicle weight class and ratio of tire wear per vehicle per hour to passenger car tire wear for a range of vehicle weights

Speed	Weight in kips					Tire Wear Ratio			
MPH	4 kip	5 kip	12 kip	40 kip	50 kip	5/4	12/4	40/4	50/4
10	.044	.047	.077	.131	.176	1.07	1.75	2.98	4.00
20	.206	.213	.348	.622	.829	1.03	1.69	3.02	4.02
30	.509	.515	.841	1.543	2.049	1.01	1.65	3.03	4.02
40	.967	.963	1.575	2.940	3.896	1.00	1.63	3.04	4.03
50	1.590	1.565	2.561	4.849	6.413	0.98	1.61	3.05	4.03
60	2.388	2.327	3.810	7.297	9.637	0.97	1.60	3.05	4.03
70	3.367	3.255	5.331	10.310	13.598	0.97	1.58	3.06	4.04
80	4.535	4.353	7.131	13.909	18.322	0.96	1.57	3.07	4.04

Speed Change Model for Tire Wear

Winfrey's passenger care tire wear data for speed changes was converted from dollars excess cost of tire wear above continuing at initial speed per 1000 speed-change cycles to units of .001 inches of excess tire wear per cycle. Curves were plotted for initial speeds of 40, 55, and 70 mph and regression models of the form $Y = A + BLnX$ fit to the curve data. The resulting intercept and regresssion coefficients for each of the three initial speed-time wear models was plotted, the model form $LnY = A + BX$ selected for both coefficients, and a regression fit developed. The model statistics are shown in Table 28 and a range of curves plotted in Figure 47.

The ratio factor needed to convert the basic passenger car speed change curve set to any vehicle weight class was developed by taking Winfrey's tire wear data for the three initial speeds 40, 55, 70 at a 40 mph speed change for 5-, 12-, 40-, and 50-kip vehicle weights and dividing these tire wear values by the 4-kip passenger car tire wear. This produced the ratios shown in Table 29. The ratio data was plotted and a linear curve fit to the points. This produced the following model:

R_w = Weight ratio factor

W = Vehicle weight in kips

$$R_w = -.64 + .16W$$

Therefore, the final series of speed change models for tire wear become:

A_s = Speed change model intercept

B_s = Speed change model regression coefficient

R_w = Weight ratio factor

Table 28. Regression statistics for speed change models for passenger car excess tire wear per cycle and for the resulting model coefficient models

Initial Speed and Tire Wear Model (.001) Inches	A	B	SE(B)	t	r	SE(est)	F Value
70 mph initial Y = A+BlnX	-.1938	.166	.006	28	.996	.014	798
55 mph initial Y = A+BlnX	-.1000	.092	.003	31	.997	.007	952
40 mph initial Y = A+BlnX	-.0489	.047	.002	21	.997	.004	457
"A" Coef. LnY = A+BX	-4.847	.046	.001	45	1.000	.022	2052
"B" Coef. LnY = A+BX	-4.703	.042	.001	31	.999	.029	936

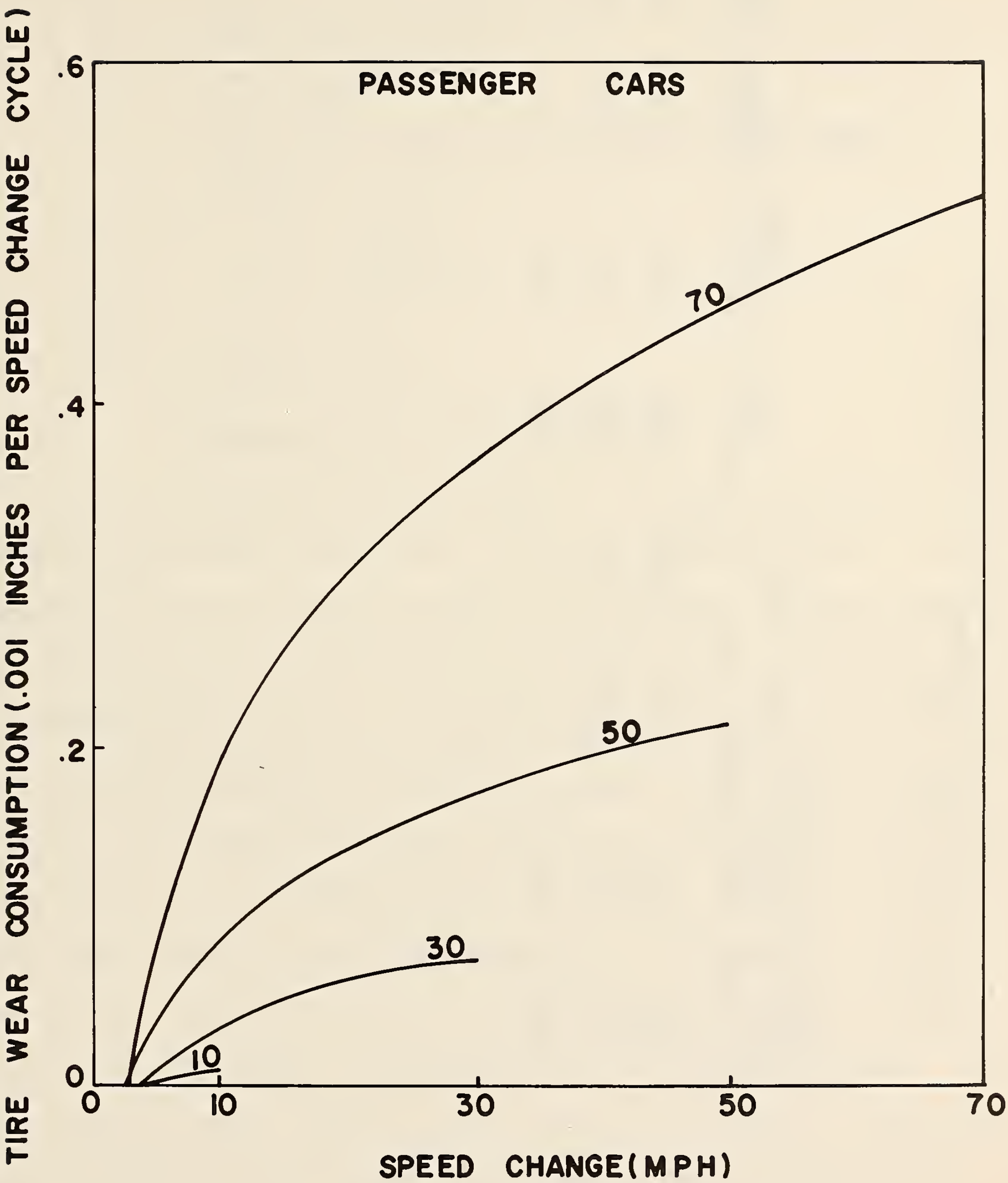


Figure 47. Excess tire wear for speed reduction for a series of initial speed curves for basic passenger car

Table 29. Ratio of excess tire wear for vehicle weights 5, 12, and 50-kips to passenger cars at 4-kips for a 40 mph speed change cycle

Initial	Vehicle weight in kips					Ratio			
	4	5	12	40	50				
Speed	Tire Wear (.001) Inches					5/4	12/4	40/4	50/4
40	.128	.136	.222	.717	.979	1.063	1.734	5.602	7.648
55	.244	.259	.424	1.366	1.867	1.061	1.738	5.598	7.652
70	.430	.457	.748	--	--	1.063	1.740	--	--

SC = Speed change in mph

S = Initial Speed

T_{sc} = Excess .001 inches of tire wear per speed change cycle

$A_{sc} = e^{(-4.85 + .046(S))}$

$B_{sc} = e^{(-4.70 + .0417(S))}$

$T_{sc} = R_w(-A_{sc} + BLnSC)$

Alignment Models for Oil Consumption

The source curves used for the set of oil consumption models was developed from Winfrey's cost tables.[48] His dollars of oil consumption were first converted to quarts of oil using his indicated unit cost by vehicle class. For the vertical alignment curve set, the oil consumption was converted from consumption per 1000 vehicle miles by speed to hourly consumption per vehicle by speed. After plotting sets of curves for all grades it was noted that the oil consumption variation by speed was very nominal as shown by Winfrey's tables. A plot of the curves revealed that not only were they not smooth but varied in shape for both positive and negative grades and also broke sharply at 60 mph for the flat grades. Rather than try to fit Winfrey's data, a smooth curve was drawn through the zero grade and the -8% and a regression analysis made to fit the plotted curve. Further, the set of curves was assumed similar for positive and negative grades. That is, the same curve set applied for +8 and -8 percent grades. Figure 48 illustrates the assumed curves developed in the regression fit.

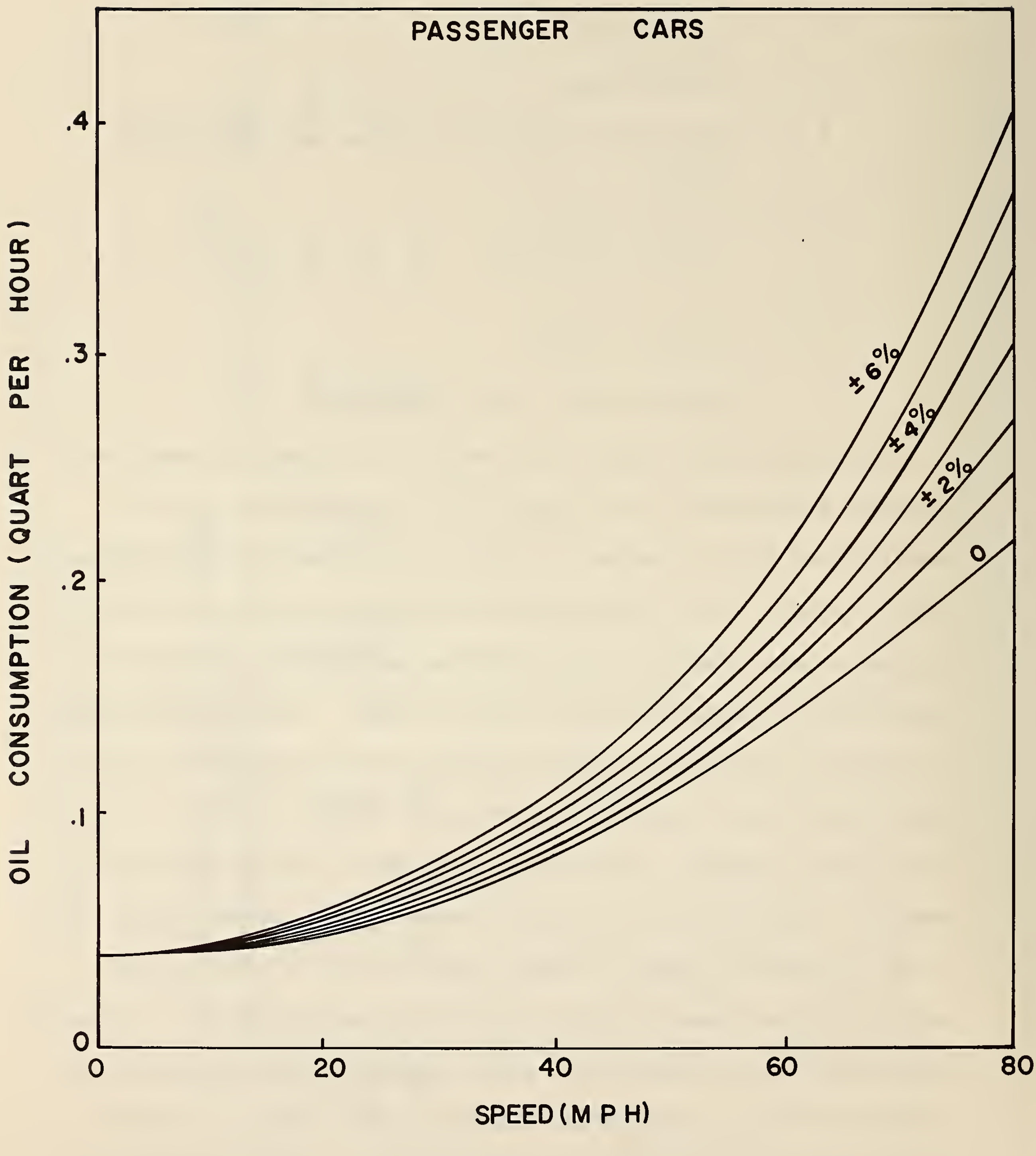


Figure 48. Vertical alignment oil consumption curves for basic passenger car

A linear model for both the A and B coefficients was established producing the following set of curves for oil consumption on grades:

A_v = Grade model intercept

B_v = Grade model slope coefficient

G = Grade in percent

O_{pc} = Oil consumption in quarts per vehicle per hour for passenger cars

S = Speed in MPH

$$A_v = -3.414 - .0184(ABS(G))$$

$$B_v = .02418 + .00142(ABS(G))$$

$$O_{pc} = e^{(A_v + B_v S)}$$

The excess oil consumption to be associated with horizontal curvature was very small. Therefore, no curve set was developed for oil consumption as a function of horizontal alignment.

For the purpose of converting the basic passenger car model set to any vehicle weight class, Winfrey's level tangents table data for oil consumption for 12-, 40-, and 50-kip commercial vehicles was divided by the 4-kip passenger car oil consumption for the speeds shown in Table 30. Table 30. An examination of the table revealed trend reversals at both the high and low speed ends. Considering the nominal variations in oil consumption, it was decided to model the 20 mph and 50 mph ratios and assume a linear trend for the entire range. The statistics for the 20 and 50 mph initial speed ratio models is shown in Table 31. The A and B coefficients were made linear as a function of initial speed. The resulting set of models is as follows:

Table 30. Ratio of oil consumption per vehicle per hour to passenger car consumption for a range of vehicle weights for level tangent sections.

	Vehicle weight in kips				Ratio		
	4	12	40	50			
Speed	Oil Consumption				12/4	40/4	50/4
10	.044	.054	.082	.167	1.23	1.86	3.80
20	.058	.080	.115	.237	1.38	1.98	4.08
30	.080	.105	.152	.305	1.31	1.90	3.81
40	.105	.124	.118	.342	1.18	1.70	3.26
50	.124	.131	.195	.330	1.06	1.57	2.66
60	.143	.187	.289	.462	1.30	2.02	3.23
70	.225						

Table 31. Regression statistics for vehicle oil consumption weight ratio models.

Speed and Ratio Model	A	B	SE(B)	t	r	SE(est)	F Value
20 MPH Y = 1/(A+BX)	.992	-.014	.003	-5	-.965	.104	27
50 MPH Y = 1/(A+BX)	1.081	-0.013	.002	-7	-.980	.071	49

A_r = Intercept for weight ratio model

B_r = Regression coefficient for weight ratio model

W = Weight of vehicle in kips

R_W = Weight ratio factor

$A_r = .93 + .003(S)$

$B_r = -.0149 + -.00004(S)$

$*R_W = 1/(A_r + B_r W)$

Speed Change Models for Oil Consumption

Winfrey's passenger car oil consumption data for speed changes was converted from dollars of excess cost of oil consumption above continuing at initial speed per 1000 speed-change cycles to excess oil consumption per vehicle speed-change cycle. Curves were plotted for initial speeds of 40, 55, and 70 mph and the two following models examined in a regression analysis:

$$LnY = A + BX$$

$$LnY = A + BLnX$$

The statistics for the final models are shown in Table 32. The coefficient A was made a linear function of speed while the coefficient B was set at 1.8 after some trial and error computations. The resulting curve set which is plotted in Figure 49 is as follows:

*Note: When the weight factor is over 50 kip, $R_W = 3W/(30 + S)$

Table 32. Regression statistics for speed change models for passenger car excess oil consumption per cycle

Initial Speed and Model	A	B	SE(B)	t	r	SE(est)	F Value
40 MPH LnY = A+LnX	-16.83	2.017	.174	12	.996	.086	135
55 MPH LnY = A+LnX	-15.01	1.700	.202	8	.973	.291	71
70 MPH LnY = A+LnX	-14.02	1.737	.105	17	.989	.257	275
Weight Ratio Model LnY = A+BLnX	- 1.347	.954	.098	10	.990	.199	94

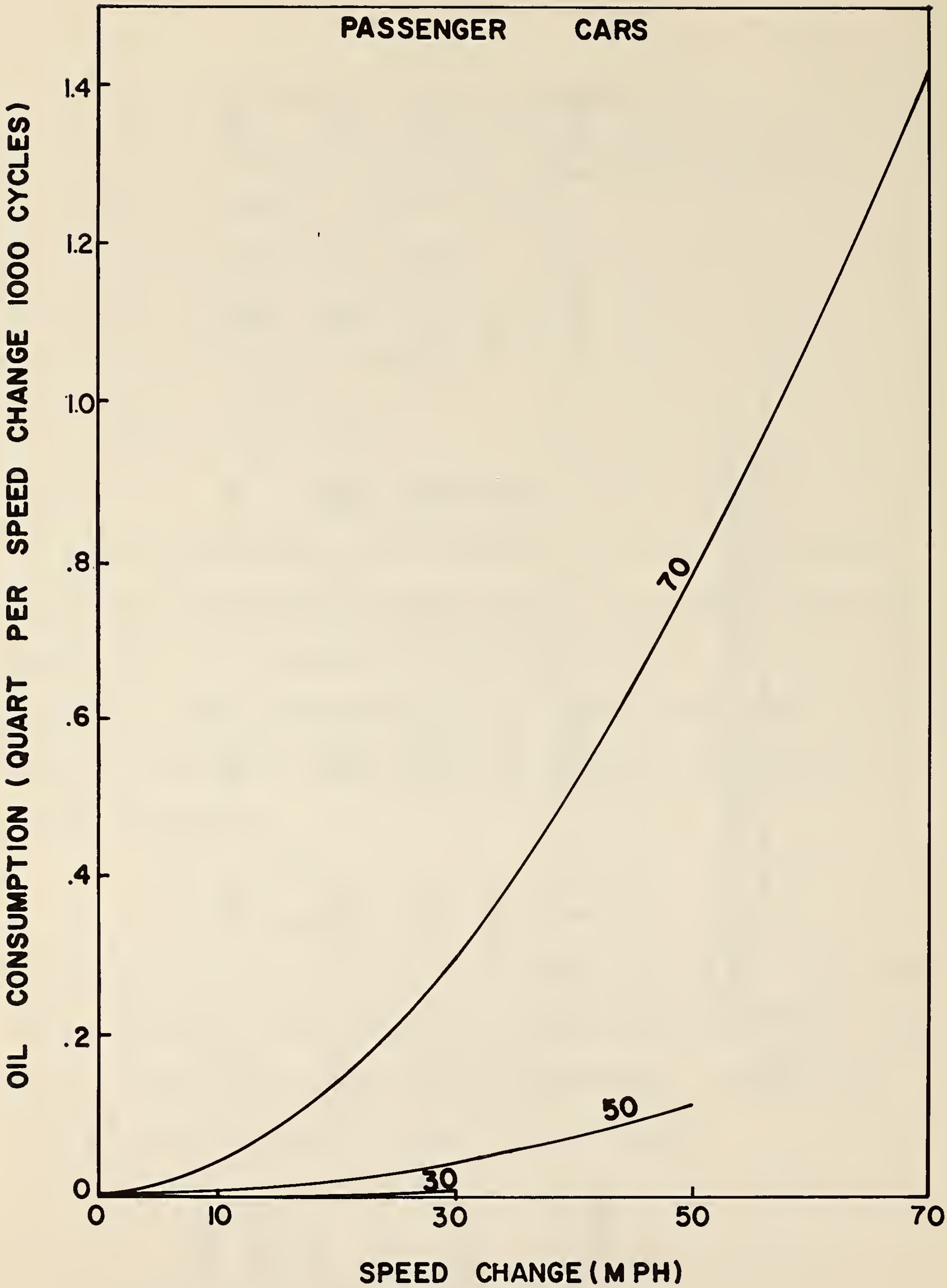


Figure 49. Excess oil consumption for speed reductions for a series of initial speed curves for basic passenger car

A_{sc} = Speed change model intercept

B_{sc} = Speed change model regression coefficient

O_{sc} = Excess quarts of oil consumed per vehicle per speed-change cycle

SC = Speed change in mph

S = Initial speed in mph

$A_{sc} = -20.5 + .09S$

$B_{sc} = 1.8$

$O_{sc} = e^{(A_{sc} + B_{sc} hu(SC))}$

A factor to convert the speed change curve set for the basic passenger car to any vehicle weight class was needed. Winfrey's excess oil consumption data for the two initial speeds 40 and 55 at 40 mph speed change for 12-, 40-, and 50-kip vehicle weights was divided by the 4-kip passenger car excess oil consumption. This produced the ratios for the speeds shown in Table 33. The ratio varied as a function of initial speed but because of the small differences in oil consumption a mean ratio was fit using the two following curve forms:

$LnY = A + BX$

$LnY = A + BLnX$

The statistics for the fit are shown in Table 32, and this model is used directly to compute the weight ratio factor (R_W) for excess oil consumption for speed change cycles.

Table 33. Ratio of excess oil consumption for vehicle weights of 12-, 40- and 50-kips to passenger cars at 4-kips for a 40 mph speed change cycle.

Initial Speed	Vehicle weight in kips					Ratio		
	4	5	12	40	50	12/4	40/4	50/4
	Excess Oil Consumption							
55	.00017	.00012	.00045	.00140	.00255	2.64	8.23	15.00
40	.00008	.00007	.00023	.00049	.00090	2.87	6.13	11.25

Alignment Models for Maintenance Cost

The source curves used for the set of Maintenance Costs models was developed from Winfrey's cost tables.[56] His dollars of maintenance costs for the vertical alignment curve set was converted from costs per 1000 vehicle miles by speed to hourly cost per vehicle by speed. After plotting sets of curves for vertical alignment, two model forms were selected for analysis. These were:

1. $LnY = A + BX$
2. $LnY = A + BLnX$

The model form and statistics for the best fitting models are shown in Table 34 for three grades. The grade coefficients A and B were plotted and it was determined that different linear models for positive and negative grades would produce a satisfactory set of models for the vertical alignment curve set. The resulting curve set is as follows:

G_p = Positive grade in percent

G_n = Negative grade in percent

A_p = Positive grade model intercept

A_n = Negative grade model intercept

B_p = Positive grade regression coefficient

B_n = Negative grade regression coefficient

M_{pc} = Dollars of vehicle operating maintenance costs per passenger car vehicle per hour of operation

S = Speed in miles per hour

Table 34. Regression statistics for vertical alignment models for passenger car maintenance costs.

Model Maint. Costs $	A	B	SE(B)	t	r	SE(est)	F Value
+8% Grade LnY + A+BLnX	-5.717	1.282	.034	37	.997	.092	1383
0% Grade LnY = A+BLnX	-5.828	1.278	.052	25	.994	.138	612
-6% Grade LnY = A+BLnX	-5.657	1.213	.056	22	.993	.148	476

$$A_p = 5.828 + .014G_p\ )$$

$$A_n = 5.828 - .0285G_n$$

$$B_p = 1.278 + .001G_p$$

$$B_n = 1.278 + .011G_n$$

$$M = e^{(-A_v + B_v LnS)}$$

A plot of the horizontal curves for maintenance cost revealed that curvature had very little influence on maintenance costs as evaluated by Winfrey. Therefore, it was decided not to create a maintenance cost model set for horizontal alignment. Figure 50 shows the vertical set.

For the purpose of converting the basic passenger car model set to any vehicle weight class, Winfrey's level tangents table data for maintenance costs for 5-, 12-, 40-, and 50-kip commercial vehicles was converted to maintenance cost per hour per vehicle and ratioed to his 4-kip passenger car data as shown in Table 35. A plot of the ratios revealed that they were a function of weight and vehicle speed and the curves were polynomials. A set of polynomial regressions were made for six speeds, the results and statistics being shown in Table 36. Each of the coefficients (A, B, and C) were plotted against speed, all curved slightly (S shape) and all reversed curvature at 20 mph. It was determined that a linear fit providing for the reversal would adequately predict the coefficients for the ratio equation. The linear models developed are as follows:

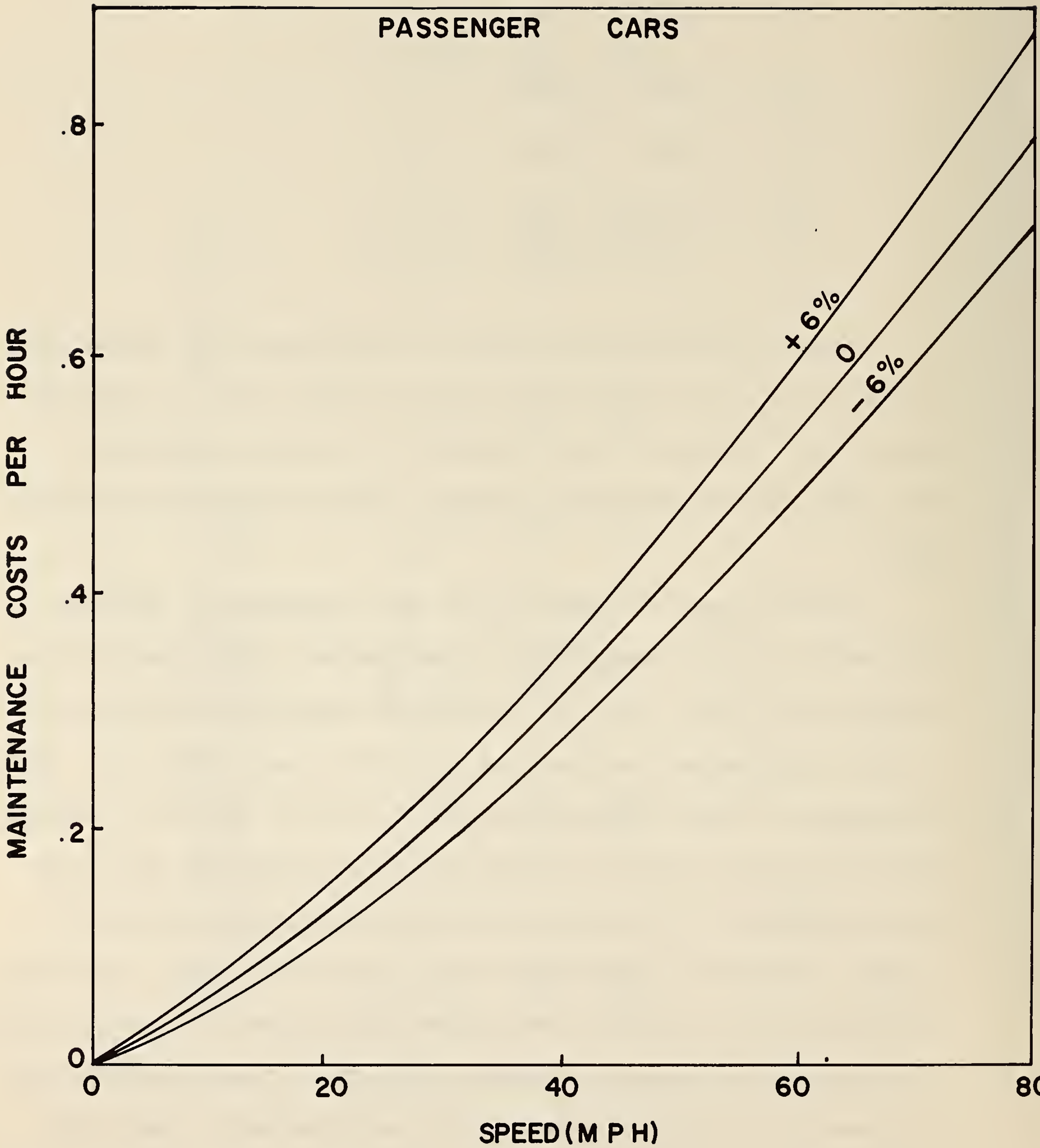


Figure 50. Vertical alignment maintenance costs curves for basic passenger car

Table 35. Ratio of maintenance cost per vehicle per hour to passenger car cost for a range of vehicle weights for level tangent sections.

Speed	Vehicle weight in kips					Maint. Cost Ratio			
	4 kip	5 kip	12 kip	40 kip	50 kip	5/4	12/4	40/4	50/4
5	.027	.033	.097	.154	.142	1.22	3.59	5.70	5.26
10	.055	.067	.189	.303	.282	1.22	3.44	5.51	5.13
20	.119	.145	.403	.644	.601	1.22	3.38	5.41	5.05
30	.198	.242	.689	1.103	1.025	1.22	3.48	5.57	5.17
40	.294	.359	1.078	1.724	1.602	1.22	3.67	5.86	5.45
50	.410	.500	1.580	2.528	2.340	1.22	3.85	6.16	5.71
60	.548	.668	2.192	3.508	3.245	1.22	4.00	6.40	5.92

Table 36. Vehicle maintenance costs weight ratio models

Speed & Ratio Model	A	B	C	SE(est)	F Value
10 MPH $Y = A+Bx+Cx^2$	-.1719	.3288	-.00451	.322	85
20 MPH $Y = A+Bx+Cx^2$	-.1384	.3201	-.00438	.314	86
30 MPH $Y = A+Bx+Cx^2$	-.1952	.3348	-.00461	.327	84
40 MPH $Y = A+Bx+Cx^2$	-.2786	.3579	-.00493	.371	75
50MPH $Y = A+Bx+Cx^2$	-.3725	.3826	-.00529	.401	72
60 MPH $Y = A+Bx+Cx^2$	-.4478	.4027	-.00558	.429	69

S = Speed in mph

A_r = Intercept coefficient for the weight ratio polynomial

B_r = 1st degree coefficient for the weight ratio polynomial

C_r = 2nd degree coefficient for the weight ratio polynomial

W = Weight of vehicle in kips

R_w = Weight ratio factor to convert passenger car maintenance cost for vertical alignment to costs for any vehicle weight.

$$A_r = .12 + .0084(ABS(S-20))$$

$$B_r = .315 + .0021(ABS(S-20))$$

$$C_r = .00438 + .000023(ABS(S-20))$$

$$R_w = A_r + B_r W = C_r W^2$$

The ratio factor R_w reflects a value of one (1) for passenger cars at 4 kips. To generalize the maintenance operation cost model for vertical alignment requires the application of the factor as follows:

$$M = R_w e^{(-A_v + B_v LnS)}$$

When W exceeds 50 the weight factor is

$$RW = 4.68 + .039 \times ABS(S-20) + .0772 \times (W-50)$$

Speed Change Models for Maintenance Cost

Winfrey's passenger car maintenance cost data for speed changes was converted from dollars excess costs above continuing at initial speed per 1000 speed change cycles to costs per cycle and plotted for the three initial speeds of 40, 55, and 70 mph. The two regression models analyzed were:

1. $LnY = A + BX$

2. $LnY = A + BLnX$

The results and model form selected are shown in Table 38.

A plot of the coefficients revealed that B was linear while A took the model for $A = A_1 + B_1LnX$. The A coefficient was modeled and the statistics are shown in Table 38.

For the purpose of converting the basic passenger car model set to any vehicle weight class, costs data for the three initial speeds of 40, 55, and 70 at a 40 mph speed change for 5-, 12-, 40-, and 50-kip vehicle weights were divided by the maintenance costs values for a basic passenger car. This produced Table 38. The ratio data was plotted and again a series of polynomial shape curves which were a function of initial speed and vehicle weight were revealed. Polynomial regressions on initial speeds produced the statistics shown in Table 39. A linear model was computed for each of the three coefficients producing the following set of models for maintenance operation costs for speed changes:

A_r = Intercept coefficient for the weight ratio polynomial

B_r = 1st degree coefficient for the weight ratio polynomial

C_r = 2nd degree coefficient for the weight ratio polynomial

W = Weight of vehicle in kips

R_W = Weight ratio factor to convert passenger car maintenance costs for speed change cycles to costs for any vehicle weight class.

S = Initial Speed in MPH

Table 37. Regression statistics for speed change models for passenger car excess vehicle maintenance cost and the intercept A for the model set

Initial Speed and Cost Model	A	B	SE(B)	t	r	SE(est)	F Value
40 MPH $LnY = A+BLnX$	-7.306	1.574	.105	15	.993	.177	225
55 MPH $LnY = A+BLnX$	-7.817	1.672	.177	9	.973	.387	89
70 MPH $LnY = A+BLnX$	-8.033	1.783	.151	12	.979	.369	140
A Coef $A = A_1+B_1LnX$	2.560	1.296	.191	7	.989	.076	46

Table 38. Ratio of tire wear for vehicle weights 5; 12; 40- and 50-kips to passenger cars at 4-kips for 40 mph speed change cycle

Initial Speed	Vehicle weight in kips					Ratio			
	4	5	12	40	50				
	Maintenance Costs					5/4	12/4	40/4	50/4
40	.24	.29	.76	1.21	1.12	1.21	3.167	5.04	4.67
55	.20	.24	.59	.95	.88	1.20	2.95	4.75	4.40
70	.24	.29				1.21			

Table 39. Vehicle maintenance weight ratio models

Initial Speed and Model	A	B	C	SE(est)	F Value
40 MPH $Y = A+BX+CX^2$	-.0557	.2952	-.00406	.274	94
55 MPH $Y = A+BX+CX^2$	+.0351	.2692	-.00368	.218	127

A_{sc} = Intercept Value for the speed change model for maintenance operation cost

B_{sc} = Regression Coefficient for the speed change model for maintenance operation cost

M_{sc} = Maintenance cost in dollars per 1000 speed change cycles

SC = Speed change in mph

$$A_r = -.298 + .00605(S)$$

$$B_r = .3642 - .00173(S)$$

$$C_r = .00506 - .000025\ (S)$$

$$R_W = A_r + B_r W = C_r W^2$$

$$A_{sc} = 2.56 + 1.30 \mathrm{Ln}(S)$$

$$B_{sc} = 1.3 + .0068(S)$$

$$M_{sc} = R_W e^{(-A_{sc} + B_{sc} \mathrm{Ln}(SC))}$$

Depreciation Model

The curve set relating vehicle depreciation to speed is based on a revised algorithm by Winfrey which he plans on incorporating in the update to his book "Economic Analysis for Highways." The algorithm is based on assuming that the annual mileage driven is a function of the speed. Specifically, Winfrey starts with an assumed reference annual mileage of 12,000 miles for passenger cars driven at 40 mph. Next, he assumes that a reduction in speed will be distributed evenly between increased hours of operation and decreased annual mileage, i.e., a reduction from 40 mph to 39 mph increases the annual hours of driving from 300 to 303.85 hours. This produces 11,849 miles annually. The process requires that the new reference mileage becomes the annual mileage for a speed of 39 mph when determining the annual mileage for 38 mph. The algorithm used to predict annual mileage as a function of speed was as follows:

M = Annual mileage

S = Speed in mph

H = Annual hours driven

1. $S = 40$
2. $H = 300$
3. $M = S \times H$
4. S = Replaced by $S - 1$
5. $H = ((M/S) - H)/2 + H$
6. Go to 3

For increasing speeds above 40 mph, the fourth step in the algorithm is changed to add 1 mph increments, i.e. $S = S + 1$. Base values of 40 mph and 300 hours were used in the execution of this algorithm for both increasing and decreasing 1 mph increments to produce Table 40. A curve was fit to the data shown in Table 40 and produced the following model which is illustrated in Figure 51:

M_a = Annual mileage for passenger cars

S = Speed in miles per hour

$$M_a = 1974\ S^{-489}$$

In the 1969 edition of his book, Economic Analysis for Highways, Winfrey presents a curve relating the number of years to scrap to annual mileage. The following model was developed to fit that curve.

Table 40. Annual vehicle mileage related to vehicle speed.

SPEED mph	MILEAGE	SPEED mph	MILEAGE
1	2326	41	12149
2	2845	42	12298
3	3414	43	12444
4	3902	44	12589
5	4336	45	12732
6	4730	46	12873
7	5094	47	13013
8	5433	48	13152
9	5753	49	13289
10	6056	50	13424
11	6344	51	13558
12	6620	52	13691
13	6885	53	13823
14	7140	54	13953
15	7386	55	14083
16	7625	56	14211
17	7856	57	14338
18	8080	58	14463
19	8298	59	14588
20	8511	60	14712
21	8719	61	14834
22	8922	62	14956
23	9120	63	15076
24	9314	64	15196
25	9504	65	15315
26	9690	66	15433
27	9873	67	15550
28	10053	68	15666
29	10229	69	15781
30	10403	70	15895
31	10573	71	16009
32	10741	72	16121
33	10906	73	16233
34	11069	74	16345
35	11229	75	16455
36	11388	76	16565
37	11544	77	16674
38	11698	78	16782
39	11849	79	16890
40	12000	80	16993

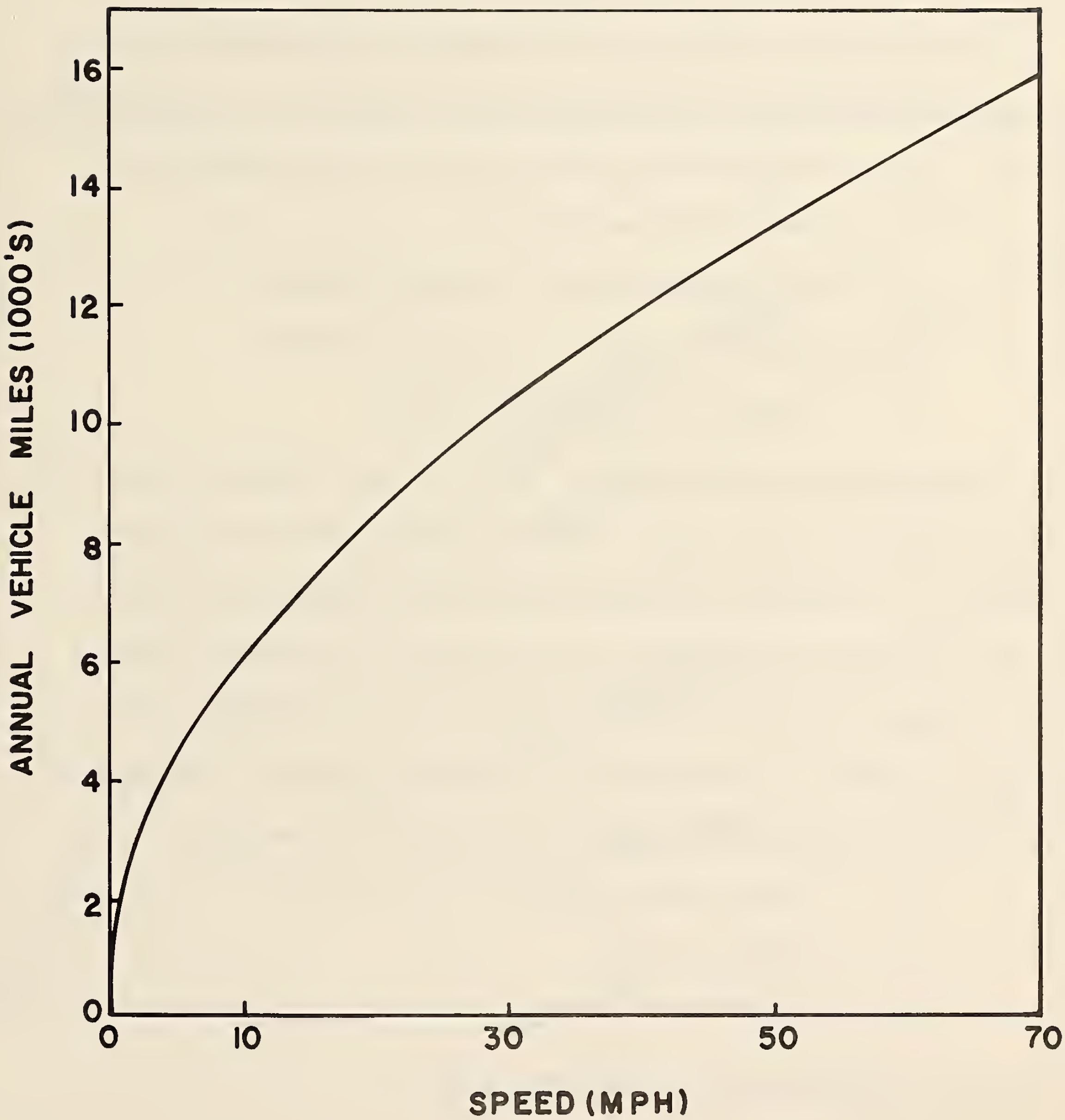


Figure 51. Annual vehicle miles as a function of speed

M_a = Annual mileage for a passenger car

Y_s = Years to scrap

$$Y_s = 47.5 - 3.88Ln(M_a)$$

Assuming that a vehicle will be completely depreciated at its scrap life permits the following depreciation model to be established:

D_p = Depreciation rate per hour of vehicle operation

S = Speed in miles per hour

Y_s = Year to scrap for a passenger vehicle

M_a = Annual mileage for a passenger vehicle

$$D_p = 1/((Y_s \times M_a)/S) = S/(Y_s \times M_a)$$

The depreciation rate will be lower for most commercial vehicles because they will have larger lifetime mileages than the passenger vehicle. The relative lifetime mileages established by Winfrey were used for vehicle life mileages. The passenger car lifetime mileage was divided by the 12-, 40-, and 50-kip vehicles lifetime mileage to produce a ratio. A curve was fit to the ratio values. This produced the following weight ratio factor to be applied to the model:

R_w = Weight ratio factor

W = Weight in kips

$$R_w = e^{(.163 - .031W)}$$

The final depreciation model becomes:

$$D = R_w D_p$$

This model is plotted in Figure 52 for a range of vehicle weights.

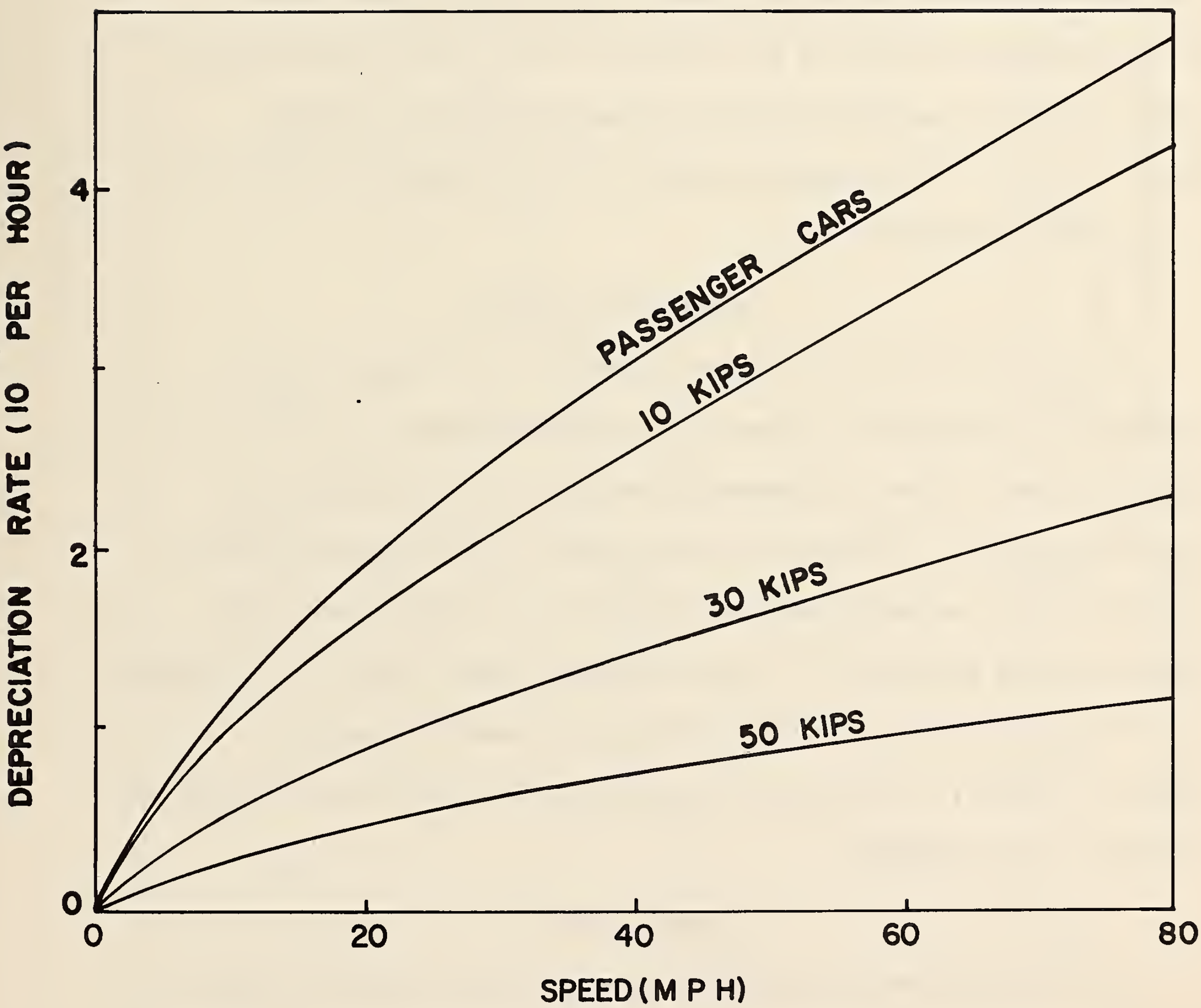


Figure 52. Depreciation rate for a range of vehicle weights as a function of speed.

Value of Time

The program computes the time lost by each vehicle through the influence zone as a function of normal speed, influence zone speed, influence zone length, and the average delay to each vehicle. The program also computes the amount of time lost in decelerating from, and accelerating to, the normal speed. This time is added to the influence zone time loss to give the total time lost by each vehicle. This time loss is multiplied by the volume affected to give the total time lost. The program assumes no time is lost for time losses of less than one-half minute.

Commercial Vehicles

The value of time for commercial vehicles is assumed to be independent of the amount of time loss as in NCHRP Report 33.[54] The default value of time for commercial vehicles is 8.72 dollars per hour per vehicle. This value is the average of the composite vehicle values of time presented in NCHRP Report 33 for 1965 updated using the increasing operation cost per mile trends taken from Trinc's Redbook of the Trucking Industry, 1971 Edition, and shown in Figure 53. The value of commercial time may be specified by the program user through an optional input statement.

Passenger Cars

The value of time for passenger cars is based on the SRI report "The Value of Time Saved by Trip Purpose[27]. In this study, the value of time is shown to be dependent on the amount of time lost and the average income of the motorist.

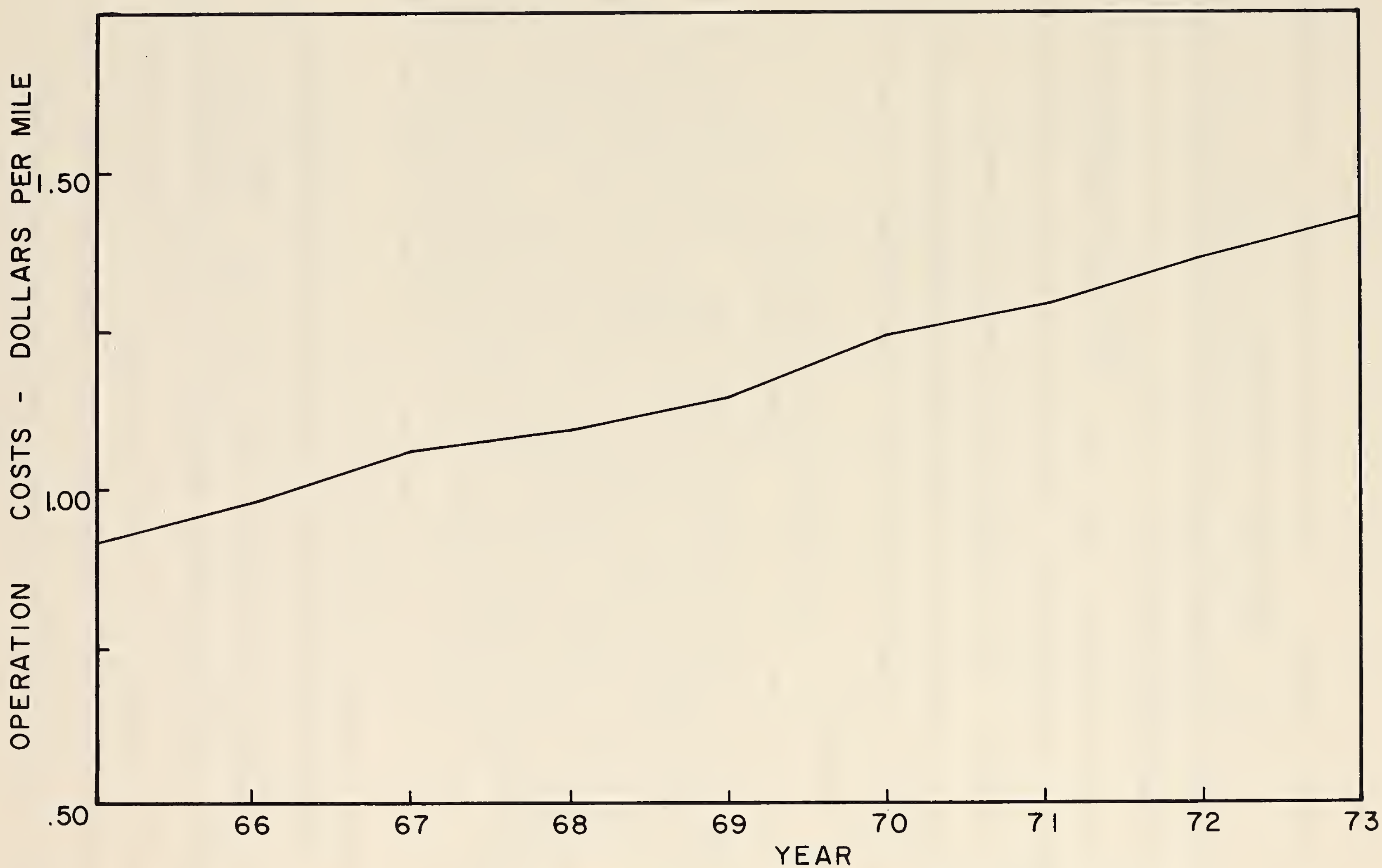


Figure 53. Trend of operation costs for commercial vehicles over an eight-year period

In developing value of time relationships SRI estimated benefits for 50th percentile motorists. Further they made the analysis for two intervals of time savings. These were 5 to 15 minutes and greater than 15 minutes. Further, SRI assumed that the benefits of any time savings between zero and five minutes were linear.

In their development of time values, the average benefit function was forced to be non-negative. This resulted in a modification to their benefit equations. When the modified benefit equations were used in this study to recreate the SRI tables, there was disagreement between our predictions and the values published in the SRI report for benefit above 15 minutes.

The modifications used by SRI in creating their tables were not available, so the following adjustments were made. First, the 50th percentile benefit equations for the first and second time interval were made equal to one another at 14 minutes by adjusting the intercept value of the second time intervals 50th percentile benefit equation. Next, a similar adjustment was made to the average benefits equation set at 14.5 minutes. These adjustments produced values that are within an accuracy of one percent of the benefit values presented in the SRI tables and are reproduced in Appendix C.

The benefit values predicted using the above defined benefit equations are expressed as dollars for given time losses. These must be converted to hourly rates before they can be used in the economic analysis to develop time costs. Additionally, to complete the "value of time" table matrix generated in the program, time losses greater than those presented in the SRI report are valued at the maximum time loss rate.

Accidents

Influence Zone Accidents

The daily number of accidents is computed for both the normal and restricted conditions in the influence zone using the following equations from NCHRP Report 47:[55]

Where

A = daily number of accidents

SL = section length in miles

V = annual average daily traffic volume

a,b,& c = the constants, shown in Table 41, which were taken from NCHRP Report 47

$$A = e^{(a+bLnSL+cLnV)}/365$$

The daily number of normal accidents in the influence zone is subtracted from the daily number of accidents computed for restricted conditions in the influence zone to produce an increased number of daily accidents. The number of increased accidents in the influence zone each hour is assumed proportional to the percent of daily traffic volume occurring in the hour.

Speed Change Accidents

The accidents occurring during the deceleration from the normal speed to the reduced speed through the influence zone are estimated using the following model, based on the data presented by Clinton L. Heimback and Harold D. Vick.[56]

Table 41. Constants of influence zone annual accidents equations taken from NCHRP Report 47.[1]

Constants	Directional Lanes Open: Freeway 1	Freeway 2	Freeway 3	Freeway 4	Detour 1	Detour 2	Detour 3
a	-4.39	-5.75	-7.26	-6.14	-4.54	-7.32	.96
b	0.51	0.76	0.77	0.68	0.59	0.67	0.99
c	0.69	0.81	0.95	0.85	0.73	1.06	0.95

[1]Kehlberg, Jaakko K. and Thorp, K. J., "Accident Rates as Related to Design Elements of Rural Highways", NCHRP Report 47, pp. 101 (1968).

AR = accident rate in accidents per million vehicle miles

AC = absolute value of the acceleration rate in miles per hour per hour

$$AR = -1.32 + .002AC$$

The acceleration rate used to estimate the accident rate in this model is a function of the normal speed, the reduced speed and the assumed distance over which this change occurs. Distance assumed for the program is one mile. This assumption was based on a study of the speed profiles created during this study.

The accident rate and traffic volume influenced is used to compute accidents. All of these accidents are counted as increased accidents since under normal conditions this speed change does not occur.

Accident Costs

The increased accidents in the influence zone and the accidents attributed to the speed change are combined to give the total increased accidents. These are costed using an average cost per accident.

The average cost of an accident used as a default in the program is based on the data in the 1971 edition of Accident Facts published by the National Safety Council.[57] This average cost is a weighted average cost of fatal, personal injury and property damage only accidents. It includes insurance administration costs, medical costs, property damage costs, and estimated wage losses. Damages awarded in excess of direct costs, police and fire protection, court costs, and indirect costs to employers are not included. The program user may specify a different average accident cost using an optional input statement.

Pollution

Motor vehicle operation is a major source of carbon monoxide, hydrocarbons, and nitrogen oxides. The exhaust emissions of carbon monoxide and hydrocarbons vary considerably with speed for gasoline motor vehicles. The U.S. Environmental Protection Agency has developed speed adjustment graphs for carbon monoxide and hydrocarbon exhaust emission factors for rural and urban travel.[58] These have been reproduced and are shown in figures 54 and 55. These factors were developed to correct emission for a composite group of vehicles operating at speeds other than some assumed average. In the analysis of the effect of roadway occupancy on pollution, these graphs are modeled and are used to develop measures of the relative change in emission rates for carbon monoxide and hydrocarbons as a percentage of non-roadway occupancy conditions. Following is shown the emission factors for gasoline-powered motor vehicles. The 1974 figures were used to establish weighting for the two speed related emissions, carbon monoxide and hydrocarbons.

	CO	HC	Total
Urban	49.7	5.28	54.98
Rural	28.0	3.72	31.72

The composite percentage developed in analysis reflects a weighting of 89% CO and 11% HC.

Regression curves were developed for both the rural and urban curves shown in both figures 60 and 61 and the resulting statistics are presented in Table 42. The coefficients of the regression curves for urban and rural highways were averaged to produce the model curves

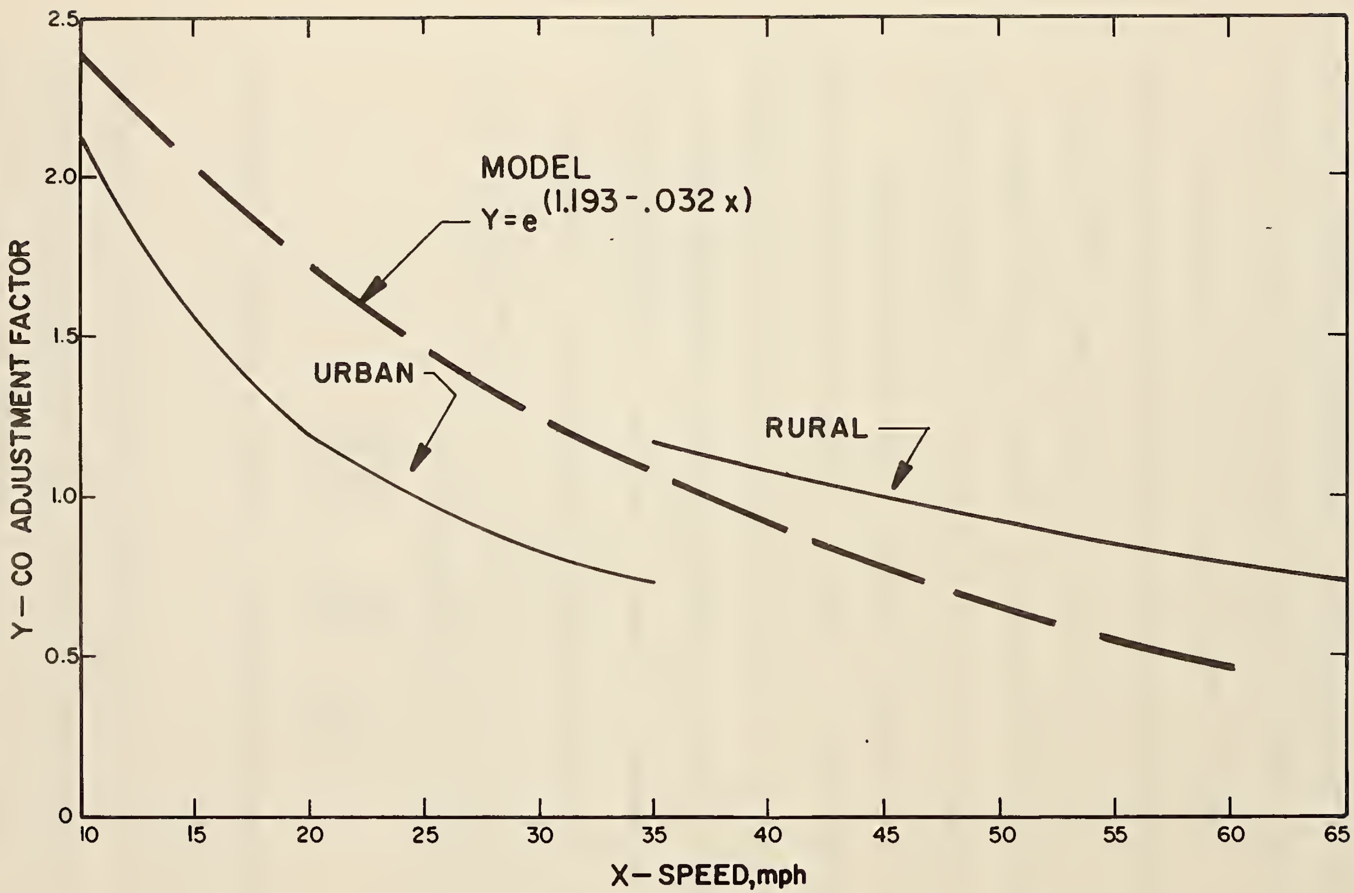


Figure 54. Pollution adjustment factor for CO emissions

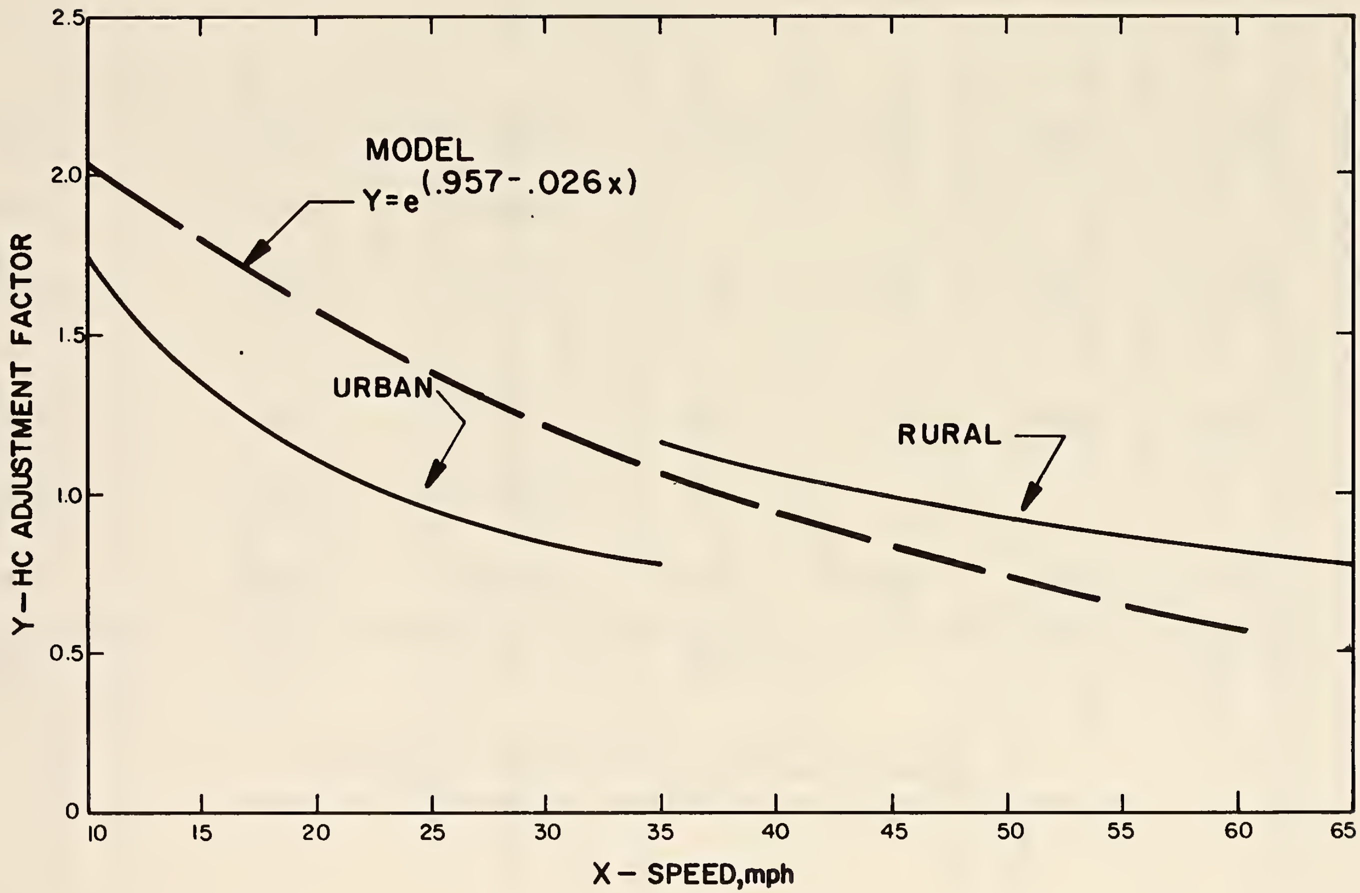


Figure 55. Pollution adjustment factor for HC emissions

Table 42. Regression statistics for CO and HC emission adjustment factors as a function of speed

Emission Model	A	B	SE(B)	t	r	SE(est)	Fvalue
HC Rural	1.099	-0.0238	.002	-12.2	-.862	.147	149
HC Model	(.957)	(-0.0255)					
HC Urban	.815	-0.0273	.002	-12.8	-.965	.161	164
CO Rural	1.309	-0.0281	.002	-13.1	-.967	.162	170
CO Model	(1.193)	(-0.0323)					
CO Urban	1.077	-0.0366	.002	-19.8	-.985	.139	391

also shown in Figures 54 and 55. These models were used in the program to predict a pollution factor for both CO and HC for both normal and roadway occupancy situations. A composite factor was developed for both related emissions based on a weighting of 89% CO and 11% HC. As an example, the following computations are made when freeway traffic is forced to slow down to pass through a freeway influence zone:

S_n = Normal hourly average speed on freeway

S_r = Hourly average speed in the influence zone

P_n = Pollution factor for normal operation on the freeway

P_r = Pollution factor for operation in the influence zone

VM = Increased vehicle miles of pollution

$$P_n = .89e^{(1.193 - .032 S_n)} + .11e^{(.957 - .026 S_n)}$$

$$P_r = .89e^{(1.193 - .032 S_r)} + .11e^{(.957 - .026 S_r)}$$

A unit was needed to express the impact of roadway occupancy on pollution. The measure selected was days of equivalent normal freeway emissions. These units are determined in the following manner:

V = Volume of traffic passing through influence zone in analysis hour

Z = Length of influence zone in miles

VM = Added vehicle miles at normal emission level

$$VM = (P_r/P_n - 1) x V x Z$$

The increased vehicle miles of pollution VM represents the traffic which would need to be added and operated on the freeway under normal conditions to produce the additional emission resulting from the reduction in vehicle speed produced by a freeway occupancy.

The total vehicle miles of additional pollution are totaled by activity and closure category for each analysis year. Then the vehicle miles are divided by the projected average daily vehicle miles to produce increased pollution days.

SUMMARY

A number of basic relationships and models have been established for use in a computer program which was designed to perform an Economic Analysis of Roadway Occupancy for Maintenance and Reconstruction (EAROMAR). A schematic illustration of the computer program EAROMAR is shown in Figure 56 where the broad program flow is illustrated. The program can be divided into four functional blocks which are:

1. initialization routine
2. pavement design interfacing
3. maintenance module
4. motorist module

The initialization block makes use of many basic relationships, models and data which are built into the program to create a series of data matrices which are needed in the execution of the program. The design interfacing block, as shown in Figure 56, interfaces with a pavement systems design program. This interface can occur annually. It permits information on traffic volume and/or pavement deterioration which is generated by the pavement design program to be used in the economic analysis. The design interfacing block also computes annual maintenance workload, establishes rehabilitation requirements, and it summarizes economic parameters generated by the analysis for transfer to the pavement systems design program or for direct output in a print routine.

The maintenance block simulates the occupancy of a roadway by work crews and establishes activity costs together with roadway occupancy

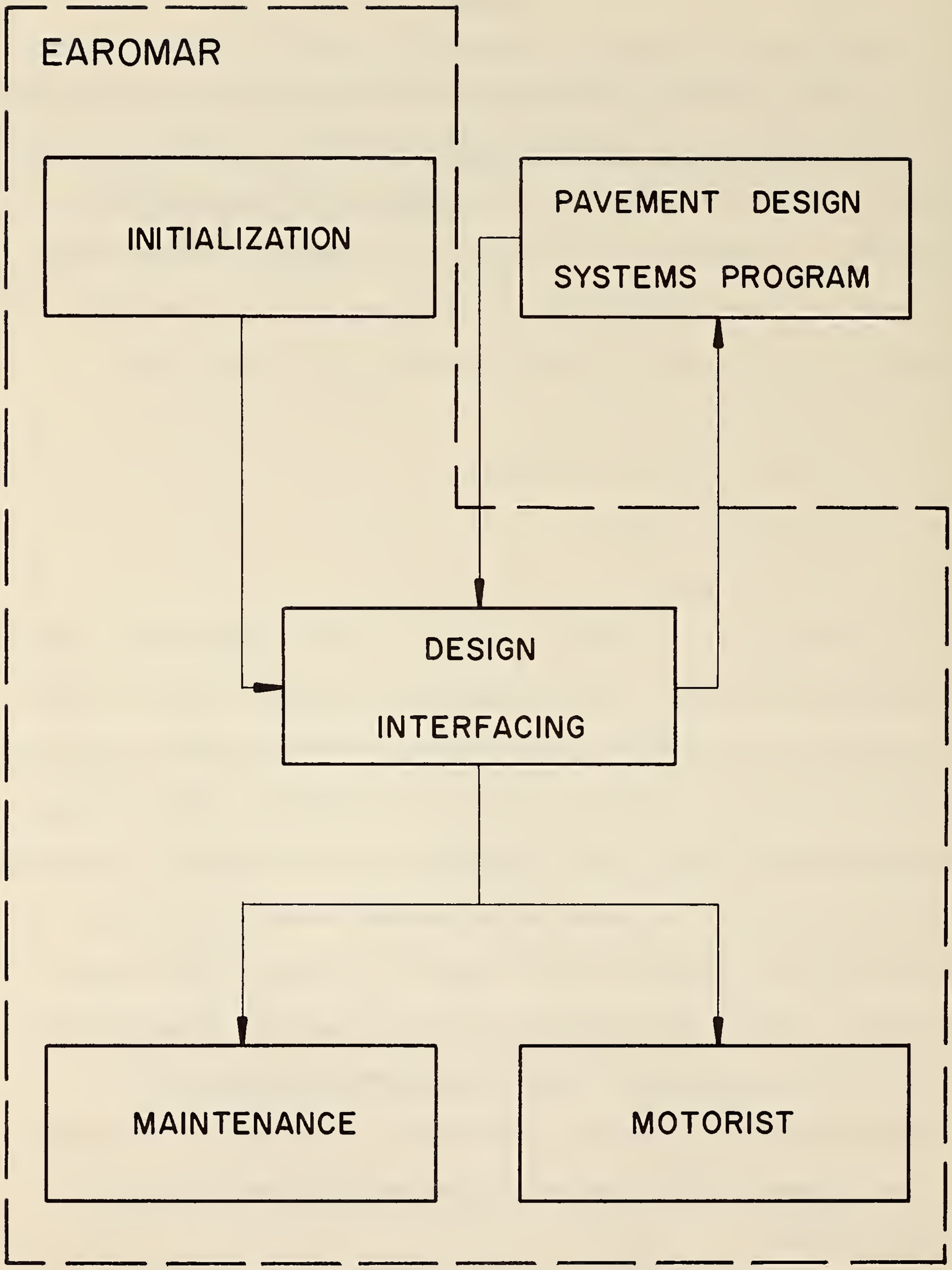


Figure 56. Broad program flow of EAROMAR showing the relationship between program blocks and the pavement design systems program

hours. These occupancy hours are used in the motorist block to determine the motorist costs associated with the roadway occupancy. These costs include vehicle operation costs, time costs, and accident costs.

EAROMAR is designed to permit an evaluation of the costs generated by a pavement design over its life for pavement maintenance and rehabilitation together with the traffic related costs created when the pavement is occupied and normal traffic flows are interrupted. To facilitate the use of EAROMAR, most of the data and all of the basic relationships and models needed to execute the program are included as program defaults. However, the program design permits a user to override essentially any default included in the program. These override options are illustrated in the detailed description of each program block which follows.

The initialization block consists of three subroutines called INITAL, OPPARA and RPRINT. A flow diagram of the block is shown in Figure 57. In Table 43 each of the following block functions is summarized in terms of program default parameters and user optional input overrides:

1. The traffic volume, directional split and commercial percentage must be input to the program by the user for both the initial and final analysis year. The program computes values for each of these parameters by year based on a linear interpolation.
2. The pavement, freeway and analysis requirements must be input to the program by the user. The pavement is described as either portland cement concrete, bituminous or composite and

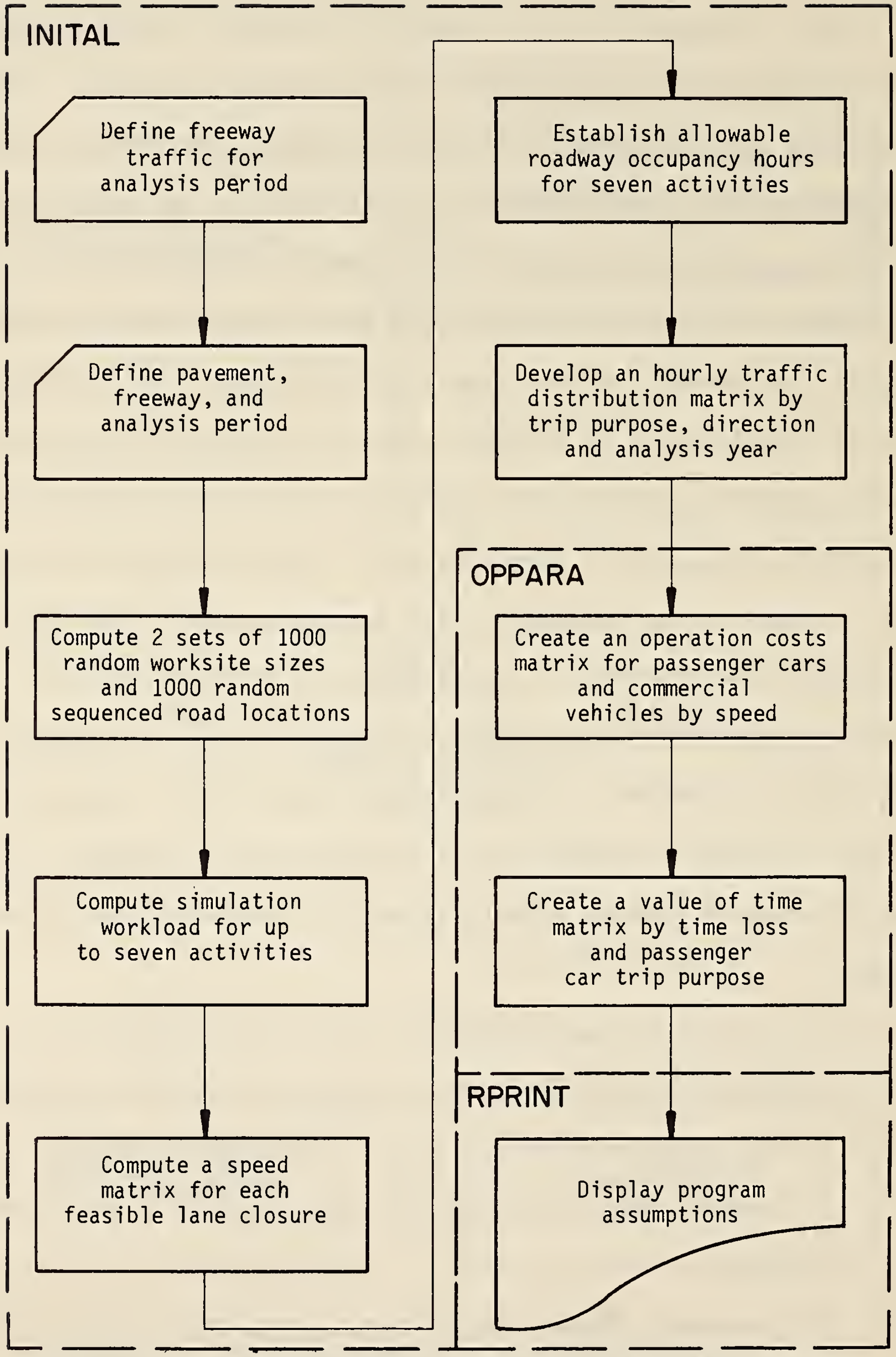


Figure 57. A flow diagram of the initialization block of program EAROMAR which includes subroutines INITAL, OPPARA and RPRINT

Table 43. Summary of program default components and input requirements and options for each of the program functions performed by the initialization block of program EAROMAR

Program Function	Program Default Assumptions	Program Input Parameters
1. Define initial and final traffic	None	Traffic volume, directional split and commercial percentage
2. Define pavement, freeway and analysis period	None	Pavement type, length, thickness, lanes, and years
3. Compute a matrix of random workside sizes and sequenced roadway locations	2 worksite size density functions, 3x1000 matrix	None
4. Compute a simulation workload for seven activities	Activity worksite descriotion, simulation iterations	Activity worksite description, simulation iterations
5. Compute a speed matrix for each feasible lane closure	V/C raio-speed algorithm, desiqn speed, lane closure capacities and speed limits	Desiqn soeed, lane closure capacities and speed limits
6. Establish allowable roadway occupancy hours for seven activities	First and last occuoancy interval hour for each activity	First and last occupancy interval hour for any activity
7. Develop an hourly traffic distribution matrix by trip purpose, direction and analysis year	Hourly distribution for all trip purposes by direction, percentaqe by trip purpose, program balancing algorithm to accommodate any input	Hourlv distribution for any trip purpose by direction, percentage of any trip purpose, directional balance
8. Create a value of time matrix by time loss and passenger car trip purpose	SRI value of time alqorithm[27] income level, vehicle occupancy	Income level, vehicle occupancy
9. Create an operations cost matrix for passenger cars and commercial vehicles by speed	Vehicle operation consumption models for fuel, oil, tires, vehicle maintenance, depreciation; pavement aliqnment, traffic composition, consumption unit costs	Pavement aliqnment, traffic composition, consumotion unit costs
10. Display program assumption	Display	Do not display

the pavement thickness is described by its surface, base and subgrade thickness. The freeway can be 4-, 6-, or 8-lane divided and any length and analysis period can be specified.

3. The computer program uses a random number generating algorithm and two worksite size density distributions to produce a matrix of random worksite sizes and roadway locations. One thousand worksite sizes are established for each of the two density distributions and the 1000 random roadway locations are sorted in ascending order.
4. The computer program computes a simulation workload for each of seven activities based on the magnitude of the workload at each worksite and the number of iterations specified for the simulation process.
5. The computer program makes use of a traffic volume/capacity ratio-speed algorithm to compute a ten point speed matrix for each feasible freeway lane closure condition. The algorithm is based on the freeway design speed and each lane closure capacity and closure speed limit.
6. Based on a definition of the first and last hours of each occupancy interval for each of seven activities, the computer program creates a matrix of available occupancy hours for each activity.
7. The computer program combines the required traffic input with any input options, fills in the voids with program assumptions and then creates a balanced matrix of the hourly distribution

of traffic by trip purpose, by direction for a base year period and a yearly increment.

8. The computer program uses the value of time algorithm developed by SRI[27] along with income level and vehicle occupancy for work and school trips and computes a matrix of the value of time by time loss and by passenger car trip purpose.

9. The computer program contains a series of vehicle operation consumption models for fuel, oil, tires, vehicle maintenance and vehicle depreciation. The models predict consumption rates as a function of vehicle speed and pavement vertical and horizontal alignment for a 4000 lb. passenger car. The consumption rate by speed is factored to reflect the weight of a typical passenger car and a composite commercial vehicle. Unit costs are applied to the resulting consumption values to create a vehicle operation costs matrix for passenger cars and commercial vehicles as a function of speed.

10. All program inputs, assumptions and generated matrices pertinent to the economic analysis are displayed in a computer printout.

The pavement systems design interfacing block controls the analysis process. This block's function is handled by subroutine YEAR in program EAROMAR. A diagram of the program flow process in subroutine YEAR is shown in Figure 58. The applicable defaults and user input options for overriding program defaults are summarized in Table 44. The functions performed by YEAR are the following:

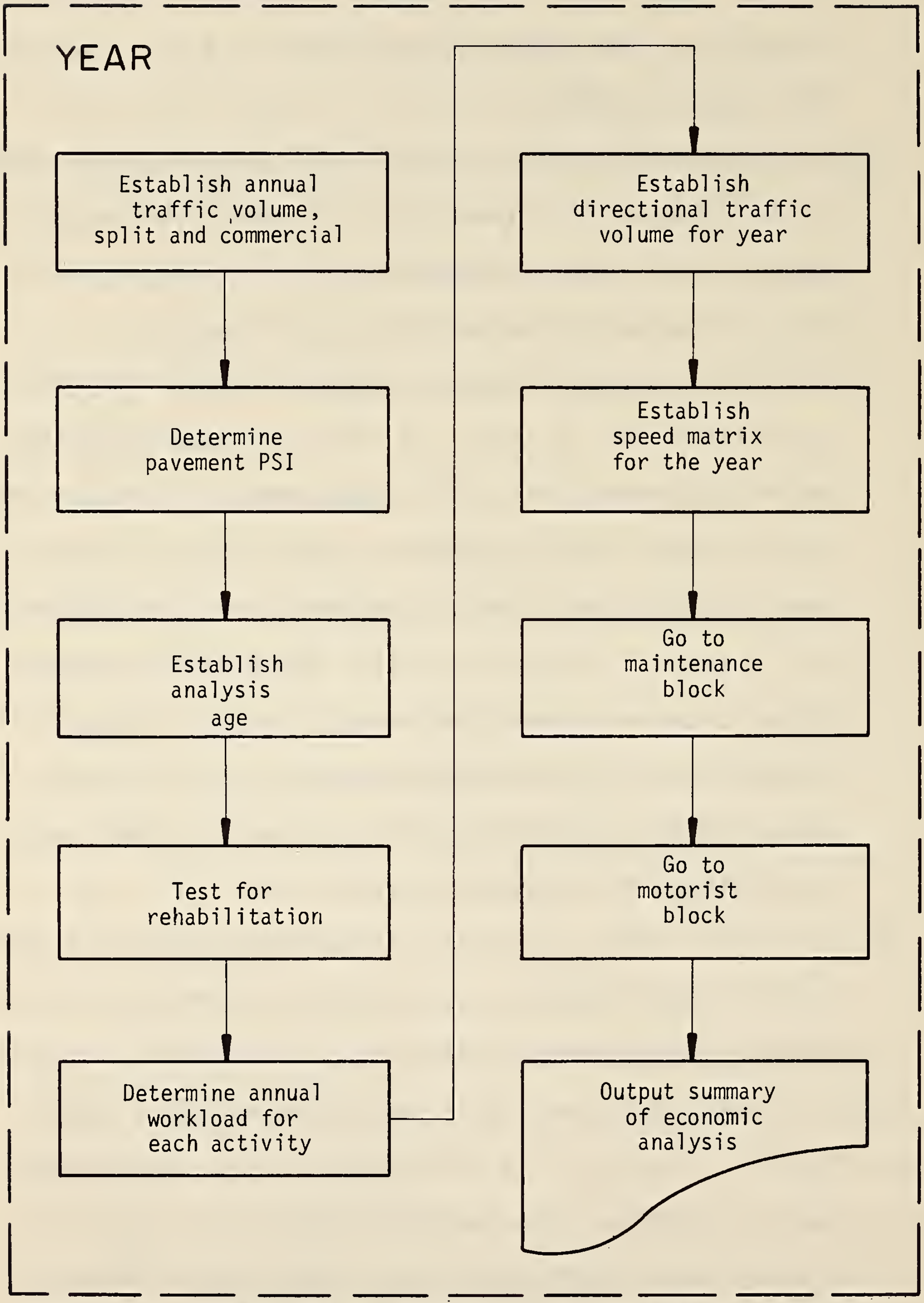


Figure 58. A flow diagram of the design interfacing block of program EAROMAR which is called subroutine YEAR

Table 44. Summary of program default components and input options for each of the program functions performed by the design interfacing block of program EAROMAR

Program Function	Program Default Assumptions	Program Input Parameters
1. Establish annual traffic volume, split and commercial traffic	Based on traffic matrix created in initialization block	None
2. Determine pavement PSI	Algorithm based on AASHO 18-kip axle predictions	Pavement systems design program input of axles or PSI
3. Establish analysis age	Analysis age is function of PSI	None
4. Test for rehabilitation	Rehabilitation when PSI less than terminal PSI	Terminal PSI
5. Determine annual workload for each activity	Activity workload models, model factors, model constants	Model factors, model constants, workload rate
6. Establish traffic volume	Based on annual traffic volume, split, and commercial	None
7. Speed matrix for the year	Based on speed matrix and v/c ratio	None
8. Go to Maintenance	N/A	N/A
9. Go to MOTORIST	N/A	N/A
10. Output summary of economic analysis	Output by activity, direction and year	Output by 1. direction, activity and year 2. activity and year 3. year 4. analysis period

1. The base year array and yearly add-on increment array created in the initialization block for: the volume of traffic, the hourly distribution of traffic by trip purpose, the directional split of traffic, and the commercial percentage of total traffic are added together for each analysis year.
2. The pavement's present serviceability index (PSI) is established for each analysis year through direct interface with the pavement systems design program or through a computation which considers the accumulated 18-kip axle loadings.
3. An analysis age is established based on the pavement's PSI. The analysis age is used in workload models which assume a pavement service life of 20 years.
4. The pavement PSI is compared with a specified terminal PSI value. When the pavement PSI becomes less than the terminal PSI value, rehabilitation is specified in the analysis year.
5. A series of activity workload models applicable to portland cement concrete, bituminous or composite pavements are used annually to compute maintenance activity workload.
6. An hourly directional traffic volume matrix is determined annually based on the annual volume, directional split and a hourly distribution matrix. The hourly volume is tested against capacity and modified anywhere the volume-capacity ratio is exceeded.
7. A directional speed is determined for each hour based on the speed matrix and the hourly volume-capacity ratio.

8. The subroutine MAINT is called and the occupancy of the roadway is simulated for each activity having a workload in the analysis year. For every feasible lane closure, the hours of roadway occupancy are established and placed in an array to be used in MOTOR. Also, maintenance costs are computed for each closure category and held in a print array.
9. The subroutine MOTOR is called and the motorist operation costs, time and time costs, accidents and accident costs, and pollution days are computed for each closure category and held in a print array.
10. The print array containing maintenance and motorist data is summarized by closure category for each direction and year, the minimum cost closure category is selected for each activity, summarized for all activities and discounted to present worth dollars and accumulated for a year to date total.

The maintenance block is subroutine MAINT which simulates the occupancy of the roadway by work crews. A diagram of the subroutine is shown in Figure 59. The program defaults and optional user inputs are summarized for the following functions in Table 45:

1. The workload and maintenance level for each activity is tested to determine if it will be performed in the analysis year.
2. The simulation parameters worksite type, random or uniform spacing and the number of simulation iterations are established for the activity.

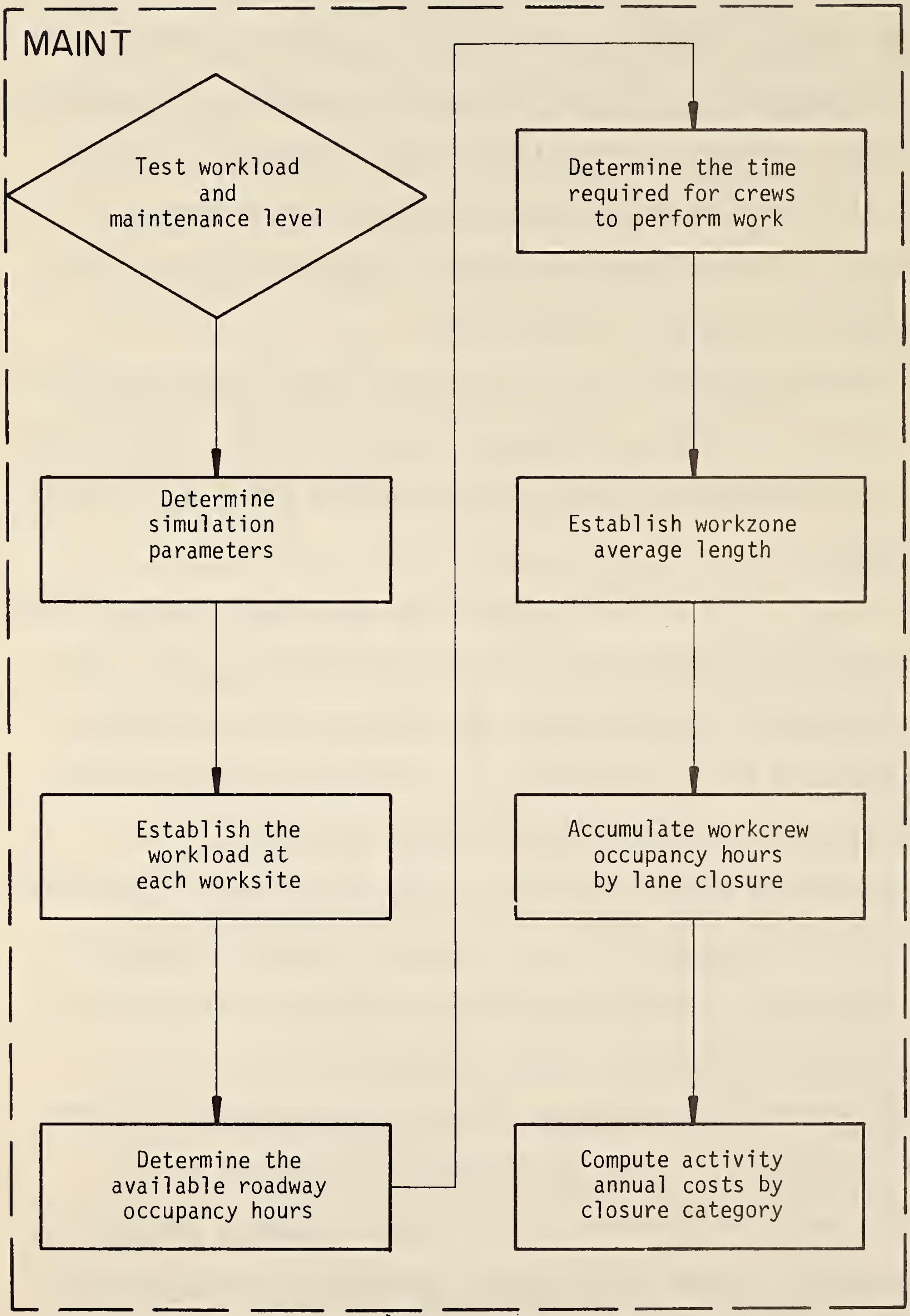


Figure 59. A flow diagram of the maintenance block of program EAROMAR which is a subroutine named MAINT

Table 45. Summary of program default components and input options for each of the program functions performed by the maintenance block in program EAROMAR

Program Function	Program Default Assumptions	Program Input Parameters
1. Test workload and maintenance level	Workload determined in YEAR, maintenance level	Maintenance level
2. Determine simulation parameters	Worksite type, worksite spacing, iterations, location spacing	Worksite type, worksite spacing, iterations, location spacing
3. Establish the workload at each worksite	Lanes closed, simulation parameters, random arrays, worksite multiplier and constant, lane width	Worksite multiplier and constant, lane width
4. Determine available roadway occupancy time for work	Occupancy hours, cure time, traffic control time, crew work hours, travel time, v/c constraints	Occupancy hours, cure time, traffic control time, crew work hours, travel time, v/c constraints
5. Determine time required for crews to perform work	Activity production rate, walking speed, travel speed	Activity production rate, walking speed, travel speed
6. Establish workzone average length	Minimum and maximum workzone length	Minimum and maximum workzone length
7. Accumulate work crew occupancy hours by lane closure	All above	None
8. Compute annual activity costs by closure category	Crew hourly costs, material unit cost	Crew hourly costs, material unit cost

3. The magnitude of the activity workload is determined at each roadway location.
4. The available roadway occupancy time is determined based on specified work hours, volume/capacity ratio constraints together with crew and activity requirements.
5. The amount of time required for work crews to complete work at a given location is computed and performed if sufficient occupancy time is available.
6. The average workzone length for an activity is determined for all workzones used in the simulation process.
7. The actual roadway occupancy hours are accumulated in days of each hour for each feasible lane closure.
8. The total activity crew hours are costed for the annual workload and held in a print array by road closure category.

The motorist block generates the traffic warrants. These warrants consist of operation, time and accident costs together with lost time, accidents and pollution impacts. A subroutine called MOTOR performs the traffic warrants analysis and a diagram of this subroutine is shown in Figure 60. The defaults applicable to MOTOR and the user input options available to modify the analysis process are shown in Table 46. These are summarized by the following subroutine steps:

1. The hourly capacity of each lane closure is computed as a function of lane closure capacity, shoulder capacity and percentage of trucks in the traffic stream.

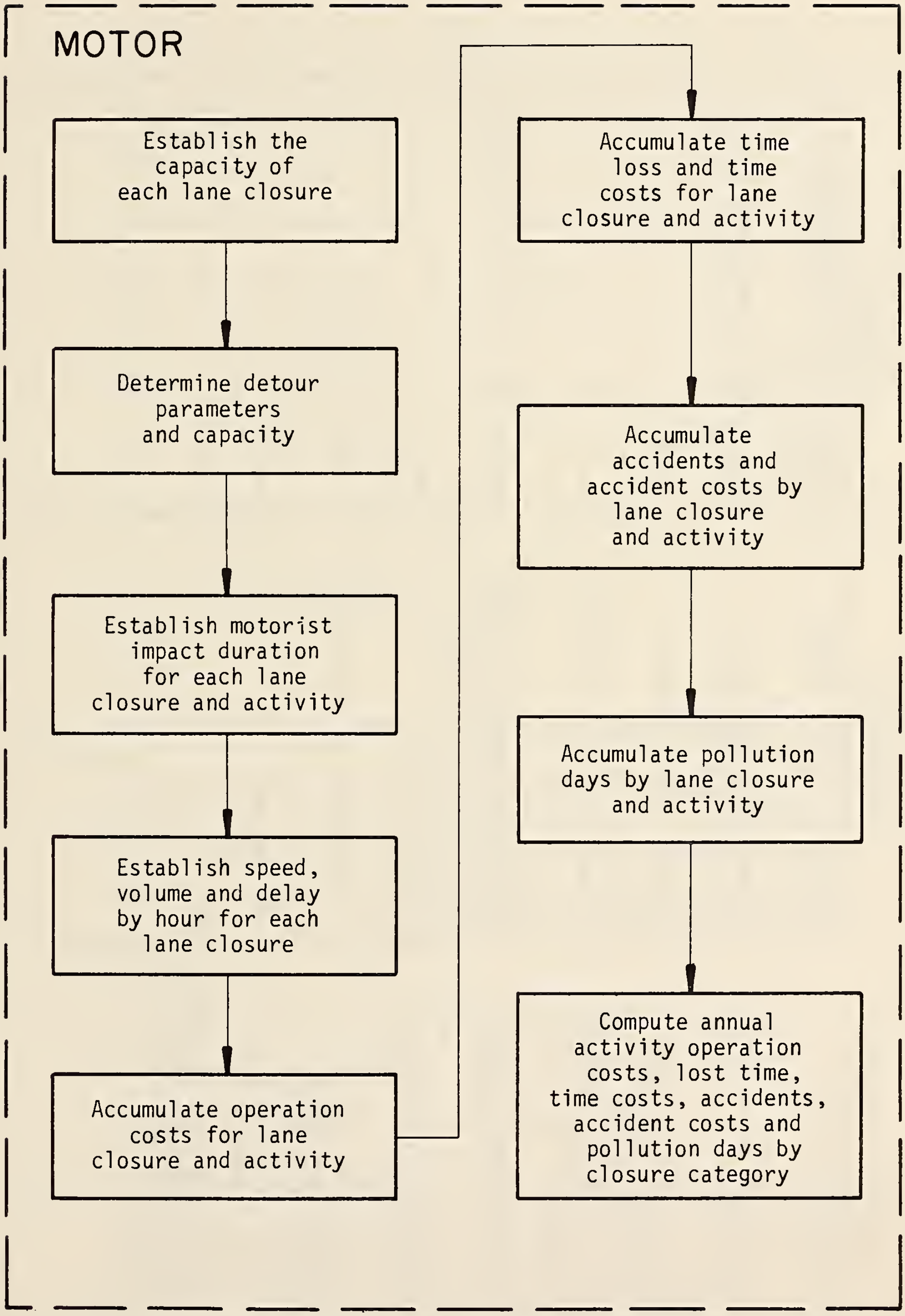


Figure 60. A flow diagram of the motorist block of program EAROMAR which is a subroutine named MOTOR

Table 46. Summary of program default components and input options for each of the program functions performed by the motorist block in program EAROMAR

Program Function	Program Default Assumptions	Program Input Parameters
1. Establish the capacity of each lane closure	Commercial vehicle percentage, lane closure capacity, shoulders open, shoulder capacity	Commercial vehicle percentage, lane closure capacity, shoulders open, shoulder capacity
2. Determine detour parameters and capacity	Distance between interchanges, detour length, speed limit, capacity, signals, lanes	Distance between interchanges, detour length, speed limit, capacity, signals, lanes
3. Establish motorist impact duration for each lane closure and activity	Occupancy matrix created in MAINT	None
4. Establish speed, volume and delay by hour for each lane closure	Volume, capacity and speed matrix, queue algorithm	None
5. Accumulate operation costs by lane closure and activity	Operation cost matrix, speed change models, unit costs fuel, oil, tires, maintenance, detour parameters	Unit cost fuel, oil, tires, maintenance
6. Accumulate the loss and time costs by lane closure and activity	Value of time matrix	None
7. Accumulate accidents and accident costs by lane closure and activity	Accident models, accident unit cost	Accident unit costs
8. Accumulate pollution days by lane closure and activity	Pollution models	None
9. Compute annual activity operation costs, accidents, accident costs and pollution days by closure category	None	None

2. The detour parameters and capacity are given program values.
3. The motorist impact duration for each roadway occupancy is determined by examining the occupancy matrix generated by MAINT.
4. The speed for each hour of roadway occupancy is determined using the speed matrix and a computed hourly volume/capacity ratio, the volume is limited to the capacity in any given hour and the delay is based on queues which develop when the actual hourly volume exceeds the capacity for the lane closure.
5. The increase in vehicle operation costs is determined by taking the difference in operation costs and speed change costs for each closure and the comparable normal operation costs in the hour.
6. The loss time is based on the difference between normal operating speed and lane closure operation speed plus any delays created when queues occur. The losses by hour by vehicle trip purpose are used with the value of time matrix to generate time costs.
7. Accident rates are computed for each lane closure as a function of lanes and deceleration rate, subtracted from normal rates which are a function of lanes and costed.
8. Pollution days are based on the number of days required to create pollution levels during normal operation equal to the increased pollution created by a lane closure.

9. The lane closure created operation costs, time losses and costs, accidents and accident costs and pollution days are grouped for closure categories, and placed in a print array to be displayed by subroutine YEAR.

As designed, the computer program EAROMAR permits traffic warrants to be developed for premium pavements. The warrant as a minimum will be based on the pavement design and traffic volume parameters specified by the user of the program together with program default data based on assumptions reflecting best present estimates.

A program run can be tailored by a user to fit any specific condition. Further, a computer run can vary from evaluating a single work activity in one year to evaluating up to seven activities for a multiple number of years.

RESULTS

Six demonstration runs were made using the program EAROMAR, an Economic Analysis of Roadway Occupancy for Maintenance and Reconstruction. A different pavement type was specified for each demonstration run. The six pavement types were 8-, 6-, and 4-lane bituminous concrete and 8-, 6-, and 4-lane portland cement concrete. The required program input as specified for each of the six pavement types is shown in Table 47.

All of the program default values were used in each demonstration run. The defaults are summarized in Volume II.

The results in terms of present worth costs are shown in Table 48.

The discontinuity in the maintenance and rehabilitation requirements for the bituminous pavements results from the rehabilitation requirements. Resurfacing occurs for the first time in the 8th, 10th and 12th years for the 8-, 6-, and 4-lane pavements respectively. With the portland cement concrete, all resurfacing occurs in the 17th year.

The accident costs are essentially a function of traffic volume. The operation and time costs are related to workload, traffic volumes and queues.

From Table 48, the total costs for the 8-, 6-, and 4-lane bituminous pavement reduce to $7.04, $7.36 and $17.62 respectively per square yard of pavement. The comparable costs for the 8-, 6-, and 4-lane portland cement concrete pavements are $1.88, $3.31 and $7.94 respectively per square yard of pavement.

Table 47. Required input as specified for 6 different pavement types in demonstration runs of the program EAROMAR

PAVEMENT TYPE	Analysis Period	Pavement Thickness	Project Length	INITIAL Volume ADT	INITIAL AM Split	INITIAL % Comm.	FINAL Volume ADT	FINAL AM Split	FINAL % Comm.
Bituminous 8-lane divided	20 yrs.	4"-10"-12"	10 miles	40,000	40%	10	200,000	50%	5
Bituminous 6-lane divided	20 yrs.	4"-10"-12"	10 miles	30,000	40%	10	150,000	50%	6
Bituminous 4-lane divided	20 yrs.	4"-10"-12"	10 miles	20,000	40%	10	100,000	50%	10
Portland Cement Concrete 8-lane divided	20 yrs.	10"-0-0	10 miles	40,000	40%	10	200,000	50%	5
Portland Cement Concrete 6-lane divided	20 yrs.	10"-0-0	10 miles	30,000	40%	10	150,000	50%	6
Portland Cement Concrete 4-lane divided	20 yrs.	10"-0-0	10 miles	20,000	40%	10	100,000	50%	10

Table 48. Results for 6 different pavement types in demonstration runs of the program EAROMAR

PAVEMENT TYPE	MAINTENANCE AND REHABILITATION COSTS*	MOTORIST COSTS*			TOTAL COSTS*
		ACCIDENTS	OPERATION	TIME	
Bituminous 8-lane divided	$1,812,201	$44,672	$779,553	$1,331,136	$3,967,590
Bituminous 6-lane divided	1,067,023	24,874	791,261	1,229,098	3,112,283
Bituminous 4-lane divided	544,993	9,564	722,866	3,686,415	4,963,862
Portland Cement Concrete 8-lane divided	398,322	23,393	268,409	369,792	1,059,941
Portland Cement Concrete 6-lane divided	303,554	18,234	448,503	629,837	1,400,154
Portland Cement Concrete 4-lane divided	199,170	5,682	328,492	1,705,109	2,238,470

*Costs in present worth dollars using 8 percent interest rate

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APPENDIX A

FIELD DATA COLLECTION

Equipment

The original field equipment for this study consisted of three cassette tape recorders, three stopwatches, and three electronic oscillators on which the frequency of the tone can be lowered or raised by closing the appropriate switches. On the observer frequency boxes both of these switches are hand-held pushbuttons. On the test car frequency box the switch for lowering the tone was replaced with photodiode circuit which is triggered by reflected light from one polished spot on the auxiliary speedometer cable.

The photodiode circuit for lowering the frequency of the tone proved to be inadequate due to multiple reflections from the speedometer cable and audio ripple in the power line which caused erroneous low frequency tones. The reflective sensing circuit was replaced with a slotted optical limit switch and rotating blade attached to the speedometer cable to solve the multiple reflections problem. At the same time the tone module was replaced with an integrated circuit timer. Zener diode protection against voltage spikes was added to solve the audio ripple problem. These modifications were made only to the test car frequency box. The circuit diagram of this frequency box is shown in Figure 61.

The tape recorders are used to record the tones from each of the frequency boxes. This establishes a time base for determining the lapse times between events which are marked with raised or lowered tones.

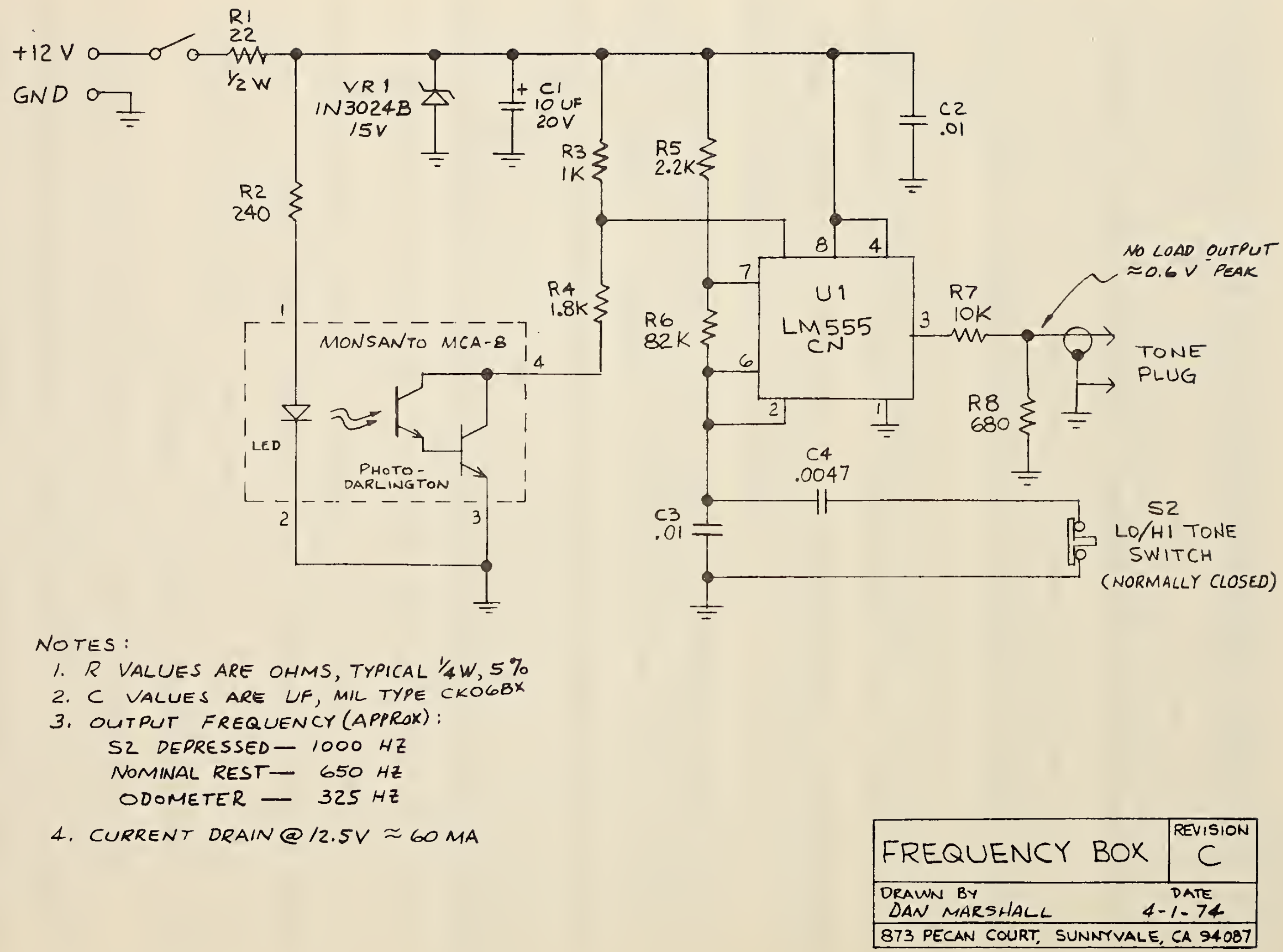

Figure 61. Circuit diagram of frequency box attached to speedometer cable of test car

The stopwatch is used to manually record the total recording time of each run. This time is used to check and, if necessary, adjust the tape recorder established time base.

Data Collection

Data was collected at a number of sites in the Washington, D. C. and San Francisco, California areas. Field data logs like the one shown in Figure 62 were made for each site. The lane closure diagrams shown in Figures 63 thru 70 were drawn using these data logs and topographic maps of the study area.

The field team for data collection consisted of three men, one test car driver and two observers. The test car driver collected speed profile and sign location data while the two observers collected volume and headway data using the following procedures:

Sign Location Run Procedure

1. Wind the stopwatch and reset to zero.
2. Switch on the microphone and verbally identify the tape as a SIGN LOCATION RUN and then the observation site number, the date, and the time of day to the nearest minute. For example, SIGN LOCATION RUN, Observation Site Number 1, November 7, 1973, 10:25 A.M.
3. Switch off the microphone and pull the microphone plug from the tape recorder and then simultaneously switch on the 1½-volt switch of the frequency box and start the stopwatch.
4. Enter the expressway.
5. Push control button to mark the location of each traffic control sign, each observer, the tiedown point and all other features in order as described on the "FIELD DATA LOG." The

FIELD DATA SUMMARY

121930 PREMIUM PAVEMENTS

OBSERVATION SITE NUMBER 1

WSAA OFFICE: FALLS CHURCH SUPERVISOR: JONES

LOCATION: I-95 NORTHBOUND BETWEEN STATE ROUTE 236 AND I-495

COUNTY: FAIRFAX STATE: VIRGINIA

REASON FOR CLOSURE: FULL DEPTH PATCHING AND JOINT REPAIR

LENGTH OF CLOSURE: 1 DAYS 8 HOURS 1/2 MILES

METHOD OF CHANNELIZATION: CONES USED FOR TAPER AND BARRELS USED TO DELINEATE ZONE

OCCUPANCY

DATE: 11/7/73 OBSERVED FROM: 9:00am TO: 5:30pm TEMP: 65°

WEATHER: SUNNY

TAPE NUMBERS:

TEST CAR	OBSERVER #1	OBSERVER #2
3 A&B	2 A&B	8 A&B
4 A&B	5 A&B	10 A&B
6 A&B	1 A	12 A
9 A&B		
11 A		

NORMAL

DATE: 11/14/73 OBSERVED FROM: 9:30am TO: 5:00pm TEMP: 45°

WEATHER: CLOUDY

TAPE NUMBERS:

TEST CAR		
7 A&B	13 A&B	15 A&B
14 A&B		

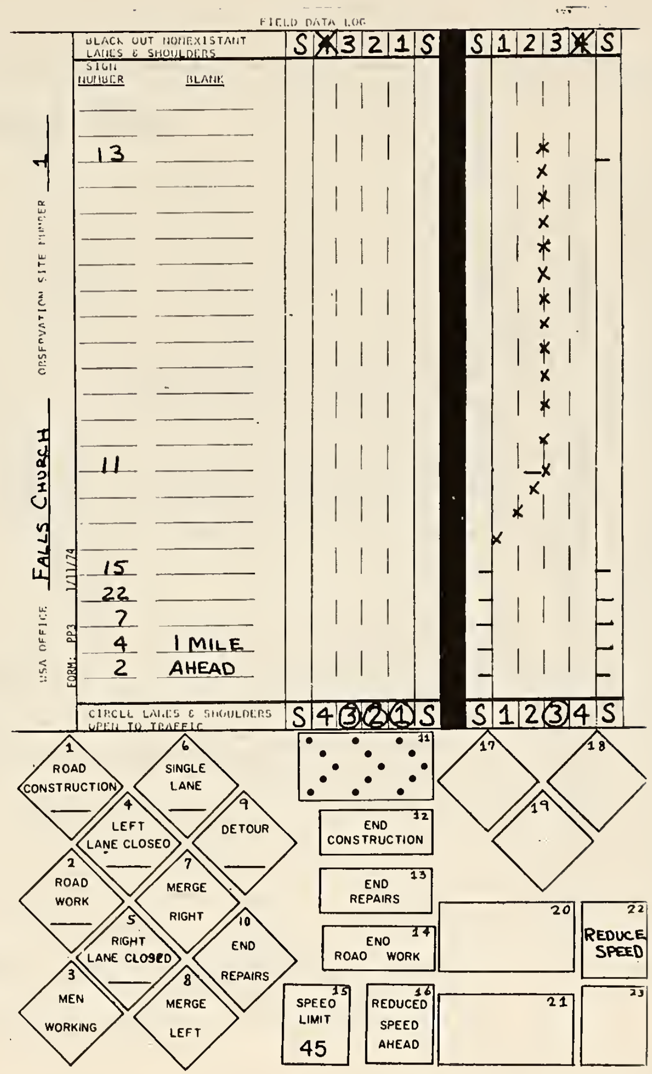

Figure 62. Example of the field data logs and summaries kept by the field teams

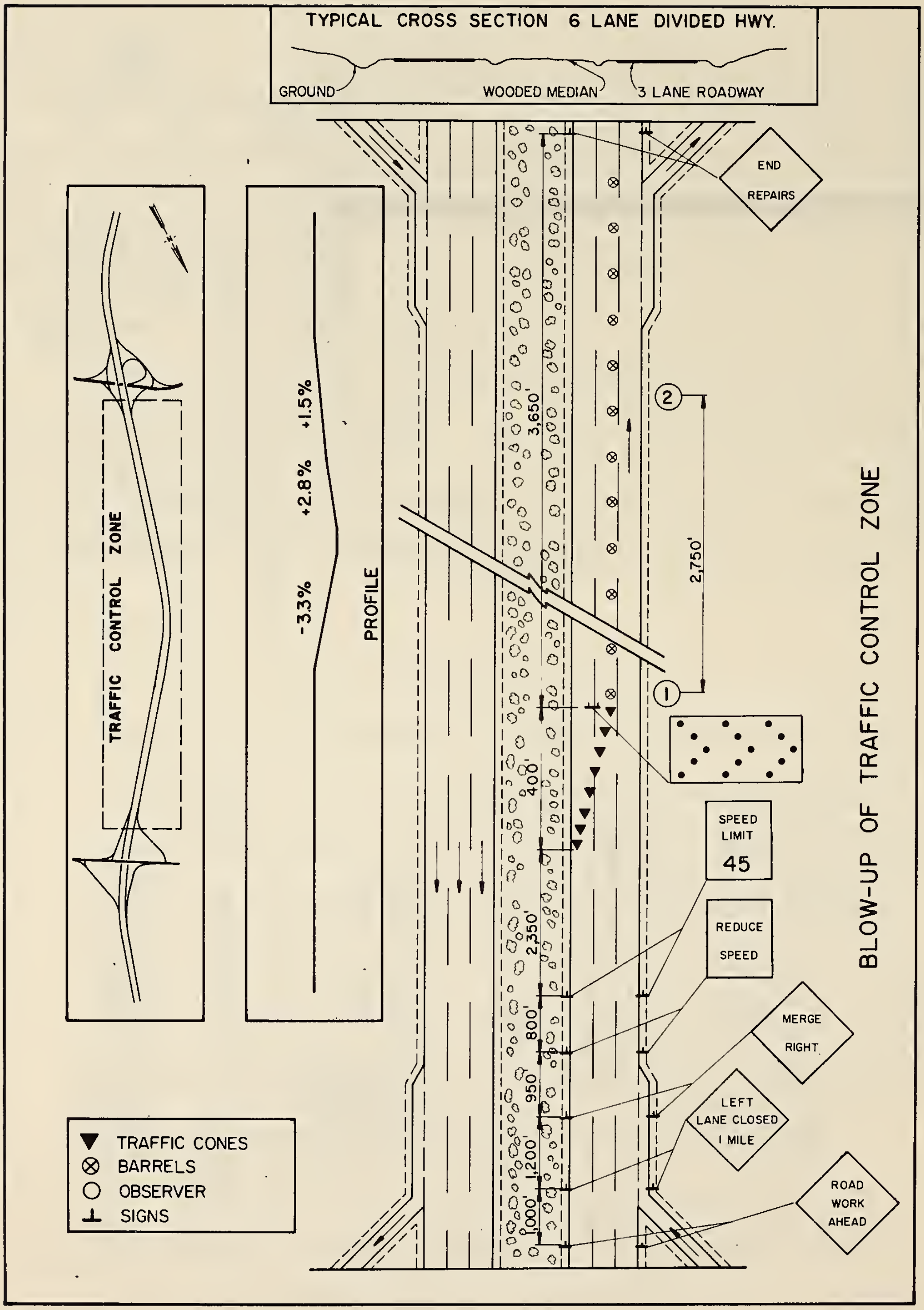

Figure 63. Lane closure diagram of observation site number 1, I-95, Prince William County, Virginia

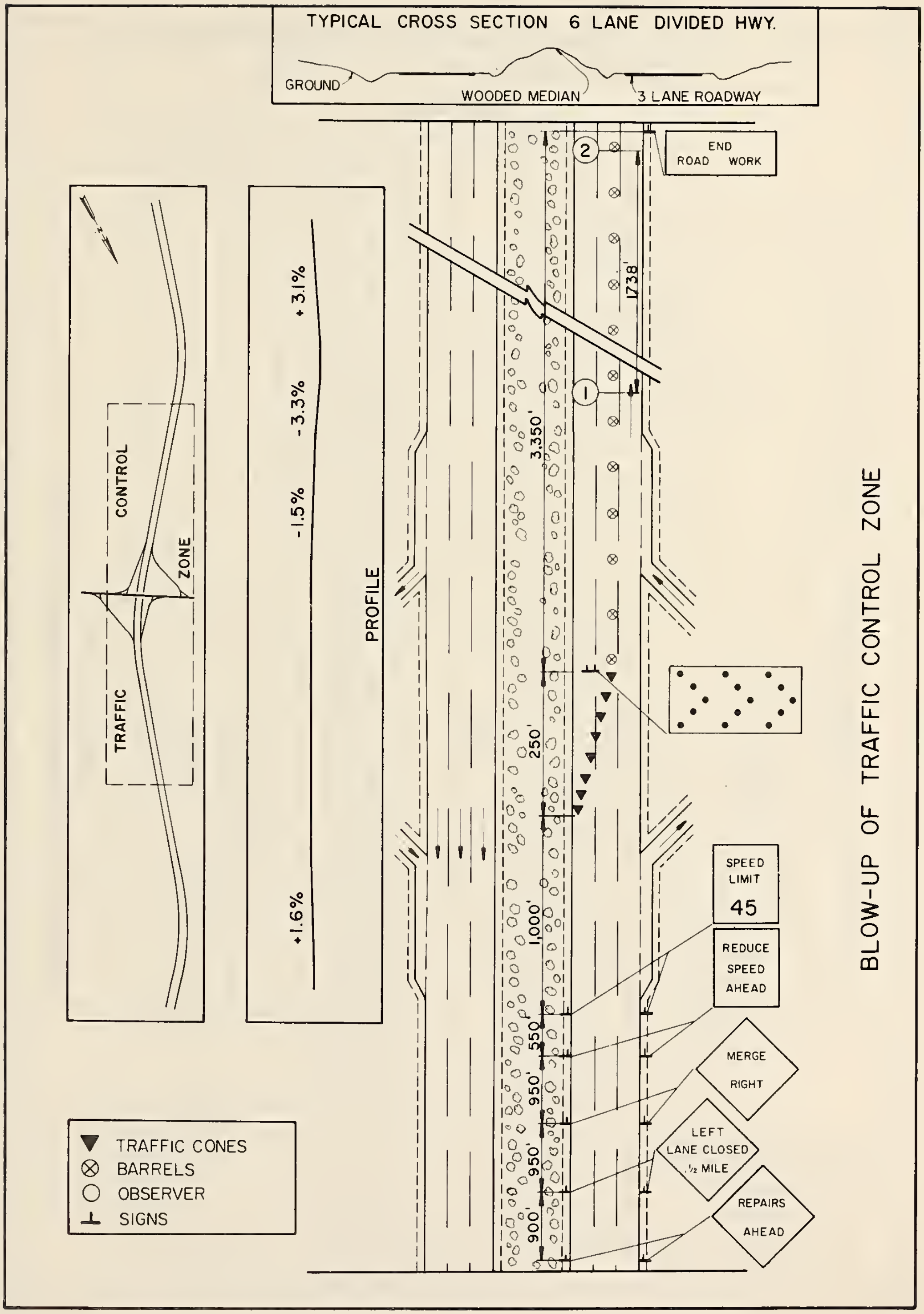

Figure 64. Lane closure diagram of observation site number 2, I-95 Prince William County, Virginia

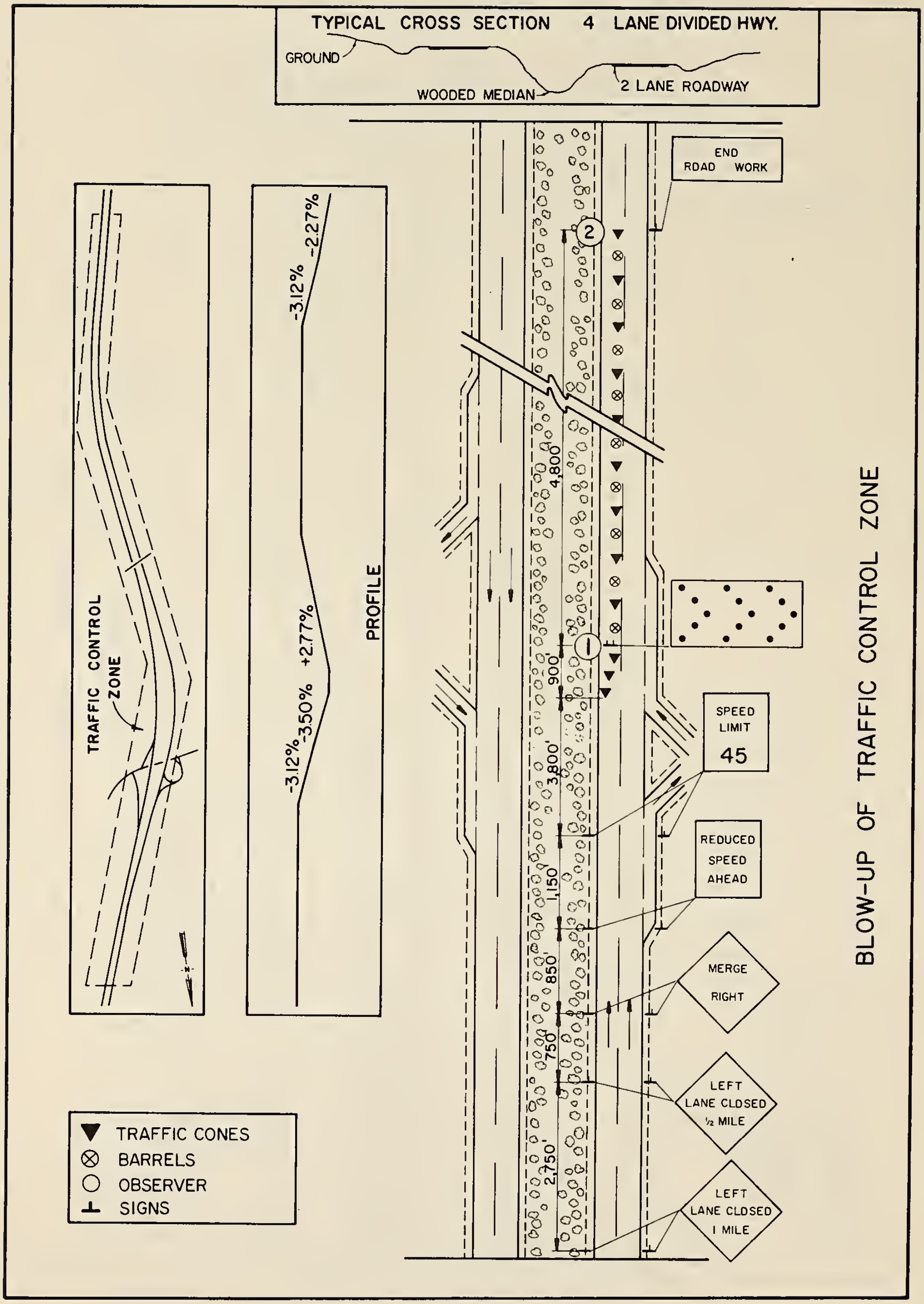

Figure 65. Lane closure diagram of observation site number 3 I-95, Stafford, Virginia

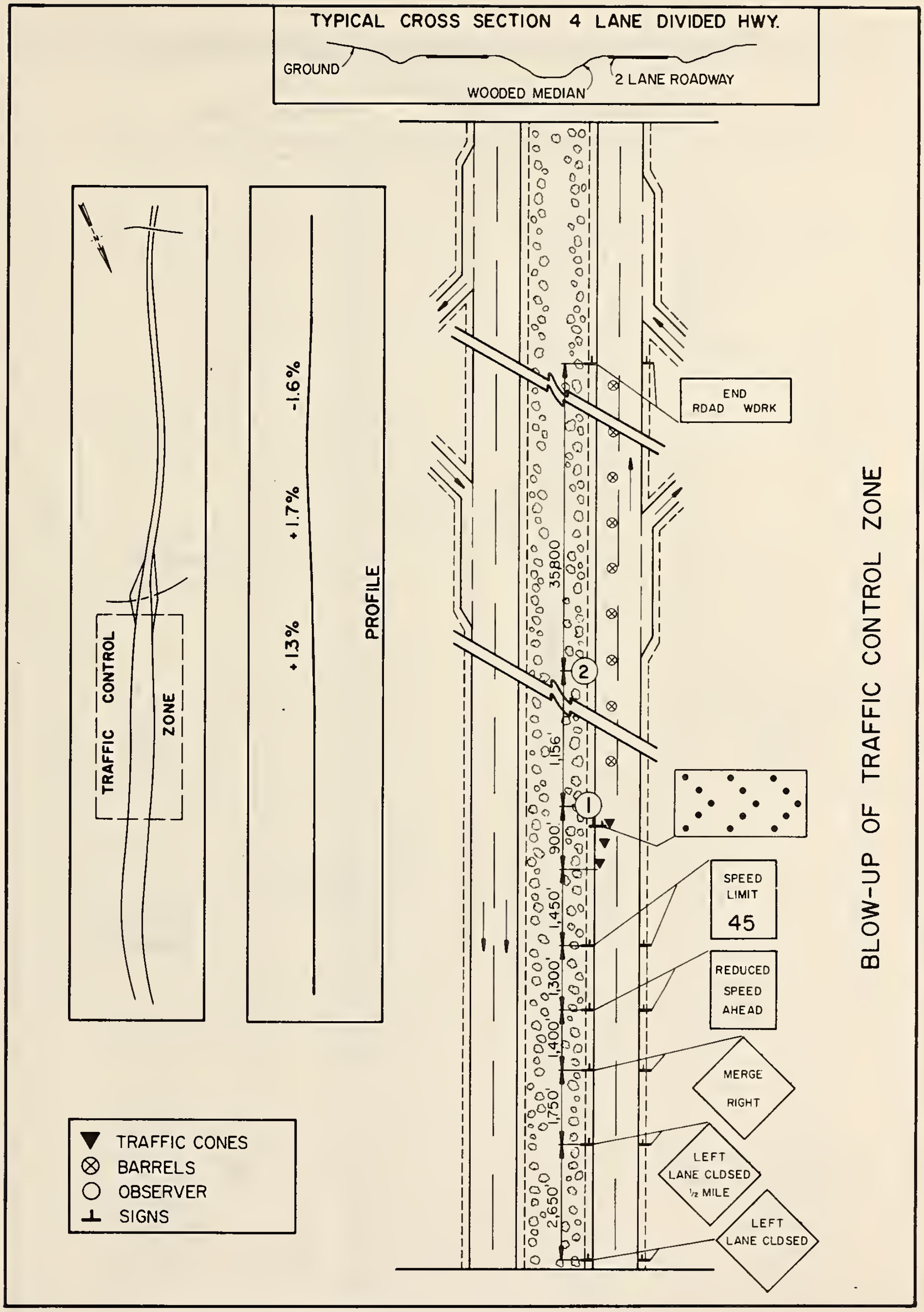

Figure 66. Lane closure diagram of observation site number 4, I-95 Stafford, Virginia

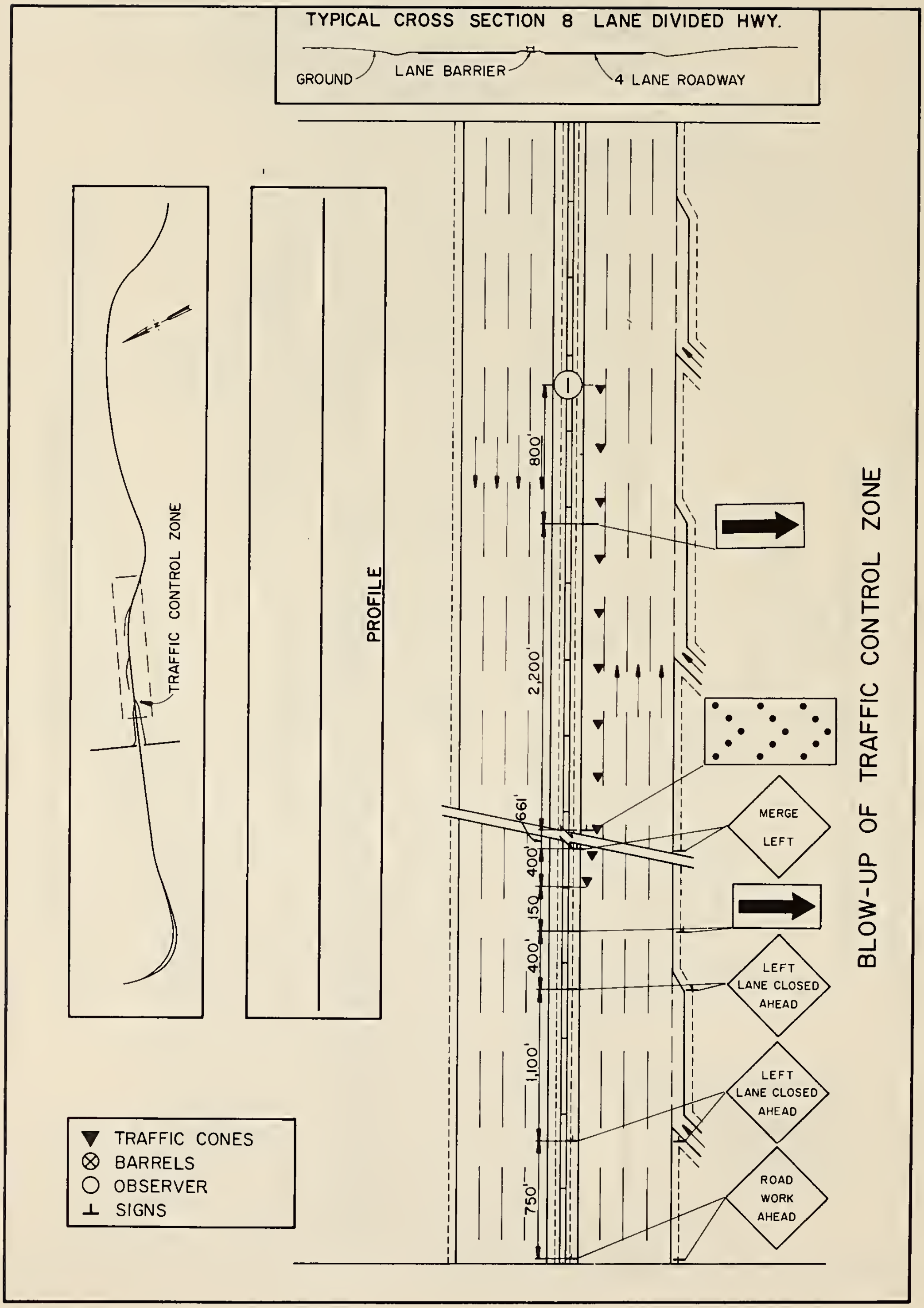

Figure 67. Lane closure diagram of observation site number 5, State Highway 17, Oakland, California

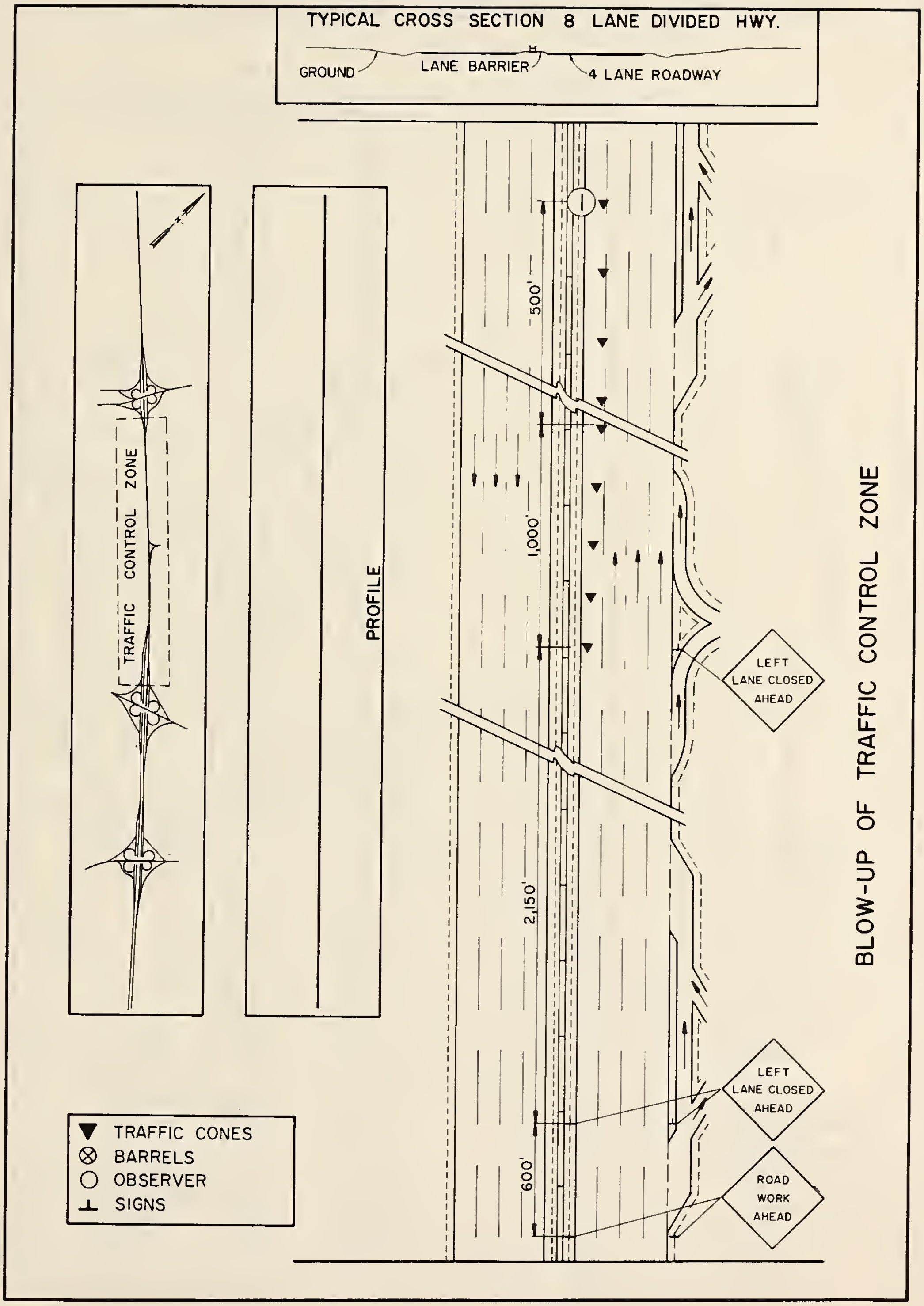

Figure 68. Lane closure diagram of observation site number 6, (1st closure), U. S. 101, San Mateo, California

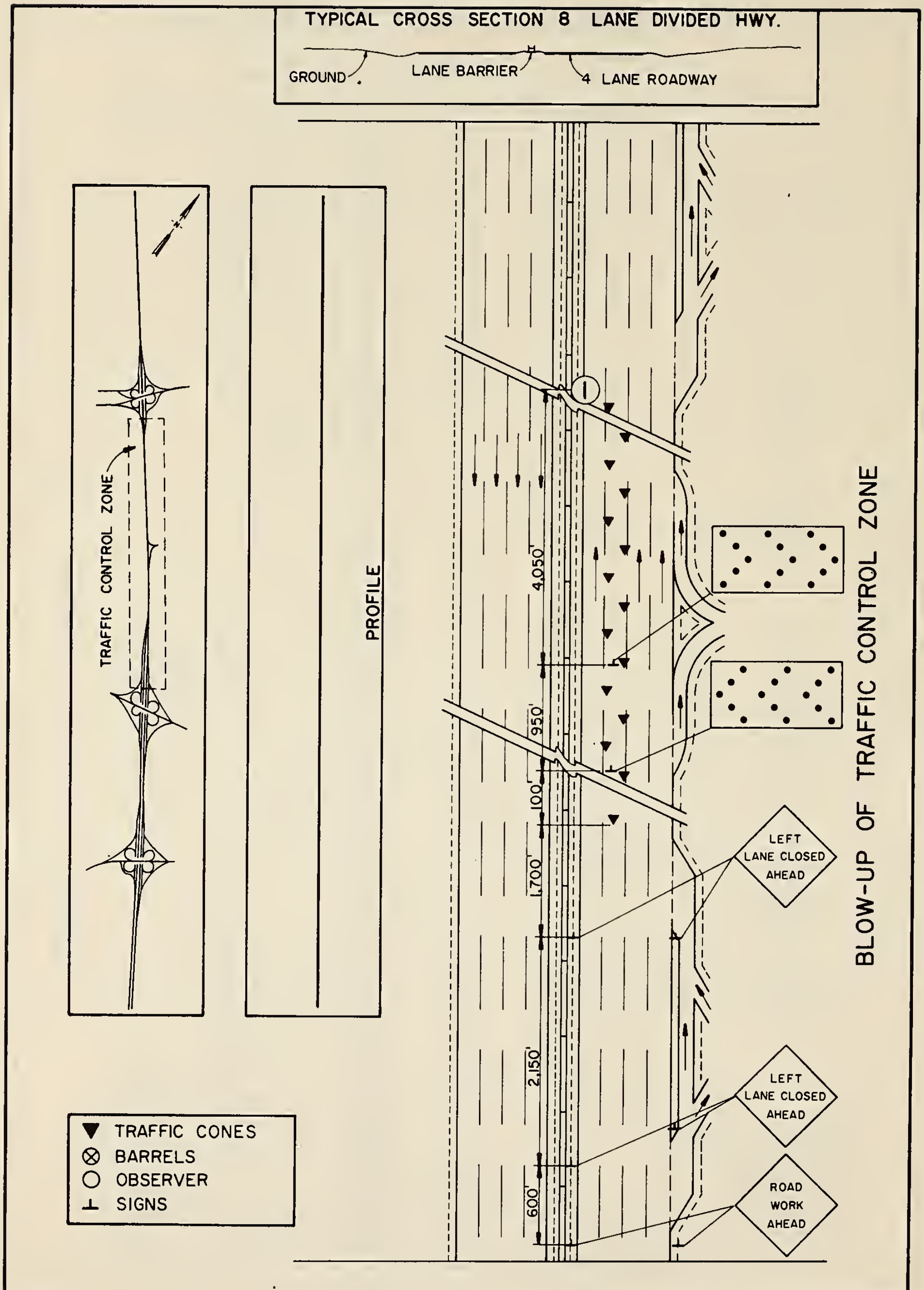

Figure 69. Lane closure diagram of observation site number 6, (2nd closure), U. S. 101, San Mateo, California

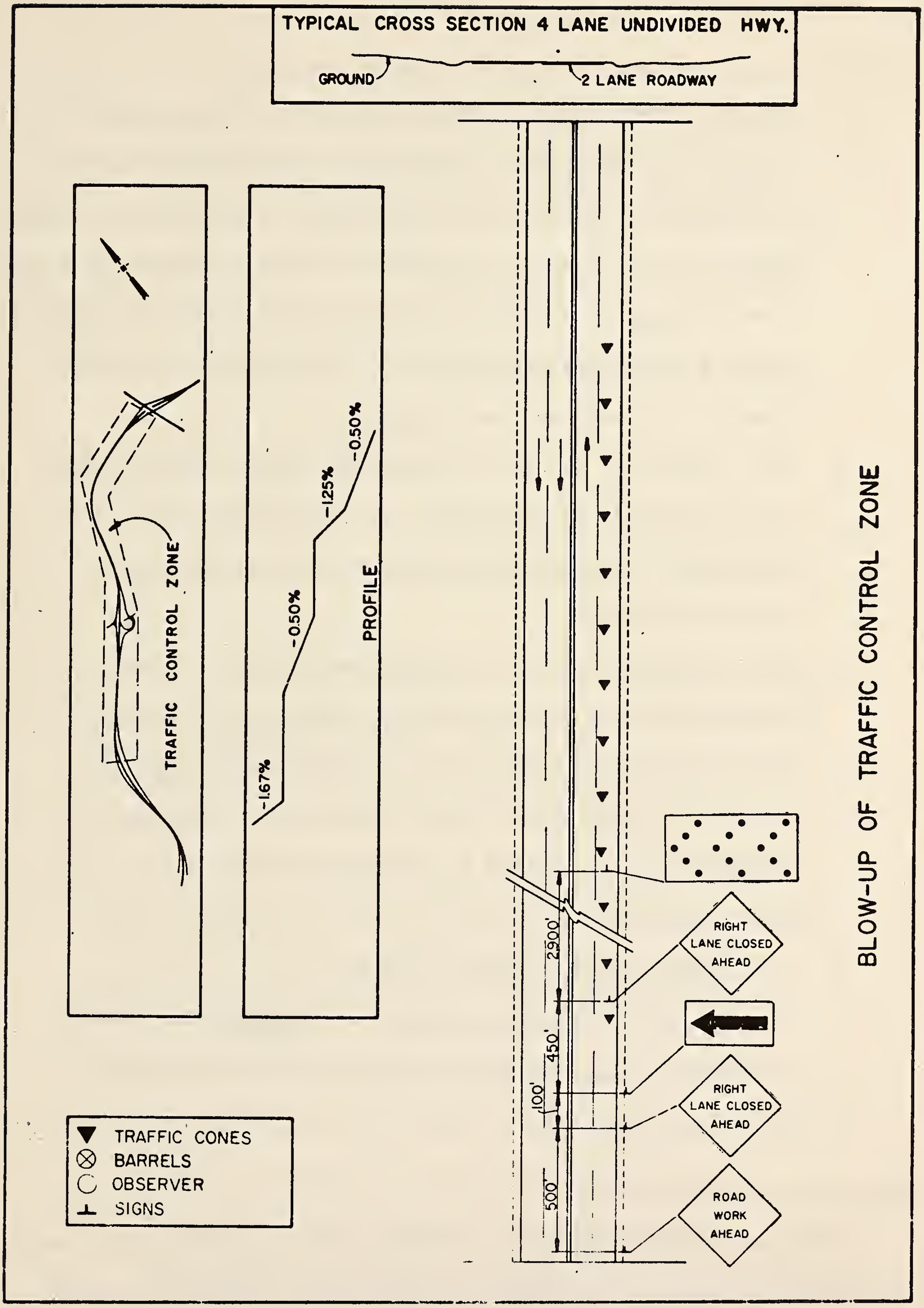

Figure 70. Lane closure diagram of observation site number 7, State route 92, San Mateo, California

distance between each of these event marks will be taken from the tape and automatically converted to stationing to be used in drawing a diagram of the lane closure. The distance between observers will be used to calculate the speeds between observers. Therefore, the observer locations should be marked when traveling at a slow speed or by actually stopping at each observer location to insure maximum accuracy.

6. After completing the pass through the traffic control zone, pull the vehicle to the side of the road and stop and then simultaneously switch off 1½-volt switch on frequency box and stop stopwatch.
7. Plug the microphone into the tape recorder, switch the microphone on and verbally describe the end of SIGN LOCATION RUN, the date, the time of day, and the elapsed time. For example, END SIGN LOCATION RUN, Observation Site Number 1, NOVEMBER 7, 1973, 10:45 A.M., lapsed time 19 minutes 46.9 seconds."
8. Push "STOP" button on tape recorder.
9. Fill out "TAPE LOG" which consists of tape cassette number, run number (S.L.), the time of day at beginning and end of run, and lapsed time.

Speed Profile Run Procedure

When the SIGN LOCATION RUN is complete and the observers have been positioned on the road, the test car driver should initiate the speed profiles. These runs should be numbered sequentially with a complete run consisting of as many passes AGAINST and THRU the traffic control zone as can be recorded on one side of a cassette tape. Further, the test vehicle driver will check the phasing of the observers. Both observers should have red hats on when they are initiating a test and off when they are completing a test. If the observers are out of phase the driver should notify them so they can get back in phase.

1. Place the clean side of a cassette tape on the recorder and rewind tape to beginning.
2. Wind and reset stopwatch.
3. Plug the microphone into the tape recorder, turn the microphone on, put recorder in record mode and waste a minute of cassette tape to pass the leader.
4. Verbally describe the cassette tape by run number, direction of first pass, date, and time to the nearest minute. For example, "RUN NUMBER 9 THRU traffic control, November 7, 1973, 2:35 P.M."
5. Turn off the microphone and pull the microphone from the tape recorder and then simultaneously switch on the 1½-volt switch on the frequency box and start the stopwatch.
6. Enter expressway and attain normal traffic flow speed.
7. Push control button to reference the speed profile on roadway.
    a. On THRU the traffic control zone passes, push the control button to indicate the passing of each observer.
       This will tie the speed profile to the observer positions on roadway and provide a measure of the elapsed time between observers.

b. On the AGAINST traffic control zone passes, push the control button to indicate the passing of the tiedown point.

8. Estimate remaining time and when there is not enough recording time left on a side of the tape cassette to record the entire next pass, either THRU or AGAINST the traffic control zone he should pull the vehicle to the side of the road, stop, and then simultaneously switch off the 1½-volt switch on the frequency box and stop the stopwatch.

9. Plug the microphone into the tape recorder, switch the microphone on and verbally describe the tape by run number, direction of last pass, date, time of day to the nearest minute, and the elapsed time. For example, "End Run Number 9, "AGAINST" traffic control, November 7, 1973, 3:15 P.M. elapsed time 39 minutes 56.2 seconds.

10. Push "STOP" button on tape recorder.

11. Fill out the "TAPE LOG" which consists of the cassette number, the run number, direction of first pass, the direction of the last pass, the time of day the tape was started, and finished, and the elapsed time.

12. Repeat steps 1-12.

Observer Procedure

1. Switch on the microphone and verbally describe the test run number, the date, and the time of day to the nearest minute, for example,

   Test Run No. 9, November 7, 1973, 10:30 A.M.

2. Switch off the microphone.
3. Put red hat on to indicate to test vehicle driver that you are prepared to collect data on this test run.
4. Watch for the test vehicle; as it comes into view pull the microphone from the tape recorder and then simultaneously switch on the frequency box and start the stopwatch.
5. As the test vehicle passes, push the red control vehicle button to indicate the passing of the test vehicle.
6. Push either the red or black button for every vehicle as it passes. Push the red button for all control vehicles and the black button for all other vehicles.
7. Remove the red hat before the test vehicle returns.
8. When the test vehicle returns, punch the red button to indicate final control vehicle. This also terminates the test run.
9. Simultaneously switch off the frequency box and stop the stopwatch.
10. Plug the microphone into the tape recorder, switch the microphone on and verbally describe the end of the test run number, the date, and the time of day to the nearest minute,

and the elapsed time. For example,

End of Test Run No. 9, November 7, 1973, 10:45 A.M., elapsed time 24 minutes and 22.3 seconds.

11. Switch off the microphone.
12. Fill out the field test run log which consists of the Test Run Number, the cassette number, the time of day the run began, and finished, and the lapsed time.
13. Reset the stopwatch to zero for the next test run.
14. Check cassette tape to make sure there is enough tape for another complete run. If not, turn cassette tape over and rewind or install new tape cassette. Make sure to waste a minute of cassette tape to pass cassette tape leader.

APPENDIX B

A series of models was developed to predict the vehicle consumption parameters fuel, oil, tires, maintenance and depreciation. Tables 49 through 67 tabulate the consumption rates for each of these parameters as a function of speed and vertical and horizontal alignment.

Table 49. Fuel, tires, oil, maintenance and depreciation in gallons, .001 inches, quarts, dollars and percent, respectively per vehicle hour for level tangent sections.

VEHICLE OPERATION PARAMETERS

SPEED	FUEL	OIL	TIRES	MAINT	DEPREC
2	0.65220	0.03454	0.00120	0.00714	0.00004
4	0.69046	0.03625	0.00563	0.01731	0.00007
6	0.73096	0.03805	0.01389	0.02907	0.00009
8	0.77383	0.03994	0.02635	0.04198	0.00010
10	0.81922	0.04192	0.04331	0.05584	0.00012
12	0.86727	0.04400	0.06498	0.07049	0.00014
14	0.91814	0.04618	0.09159	0.08584	0.00015
16	0.97200	0.04847	0.12329	0.10181	0.00016
18	1.02901	0.05087	0.16025	0.11835	0.00018
20	1.08937	0.05340	0.20260	0.13541	0.00019
22	1.15327	0.05605	0.25049	0.15295	0.00020
24	1.22091	0.05882	0.30402	0.17094	0.00021
26	1.29253	0.06174	0.36332	0.18935	0.00023
28	1.36834	0.06480	0.42848	0.20816	0.00024
30	1.44860	0.06802	0.49961	0.22735	0.00025
32	1.53357	0.07139	0.57679	0.24690	0.00026
34	1.62352	0.07493	0.66013	0.26679	0.00027
36	1.71875	0.07865	0.74970	0.28700	0.00028
38	1.81957	0.08255	0.84558	0.30754	0.00029
40	1.92630	0.08664	0.94785	0.32837	0.00030
42	2.03928	0.09094	1.05659	0.34950	0.00031
44	2.15890	0.09545	1.17187	0.37091	0.00032
46	2.28553	0.10018	1.29376	0.39259	0.00033
48	2.41959	0.10515	1.42232	0.41453	0.00034
50	2.56152	0.11036	1.55762	0.43673	0.00035
52	2.71176	0.11583	1.69973	0.45918	0.00036
54	2.87082	0.12158	1.84869	0.48187	0.00037
56	3.03921	0.12761	2.00457	0.50480	0.00038
58	3.21748	0.13394	2.16744	0.52795	0.00039
60	3.40620	0.14058	2.33733	0.55133	0.00040
62	3.60600	0.14755	2.51432	0.57492	0.00041
64	3.81751	0.15487	2.69844	0.59873	0.00042
66	4.04143	0.16254	2.88975	0.62274	0.00043
68	4.27848	0.17061	3.08830	0.64696	0.00044
70	4.52944	0.17907	3.29415	0.67138	0.00044
72	4.79512	0.18795	3.50734	0.69599	0.00045
74	5.07638	0.19727	3.72791	0.72079	0.00046
76	5.37414	0.20705	3.95591	0.74578	0.00047
78	5.68937	0.21732	4.19139	0.77095	0.00048
80	6.02308	0.22809	4.43439	0.79631	0.00049

Table 50. Fuel, tires, oil and maintenance in gallons, .001 inches, quarts and dollars respectively per vehicle hour for tangent sections with +1% grade

VEHICLE OPERATION PARAMETERS

SPEED	FUEL	OIL	TIRES	MAINT
2	0.70839	0.03401	0.00132	0.00724
4	0.76008	0.03580	0.00613	0.01758
6	0.81054	0.03768	0.01505	0.02953
8	0.86217	0.03966	0.02847	0.04266
10	0.91583	0.04174	0.04666	0.05676
12	0.97198	0.04394	0.06988	0.07166
14	1.03094	0.04625	0.09832	0.08728
16	1.09301	0.04868	0.13216	0.10353
18	1.15842	0.05124	0.17156	0.12037
20	1.22741	0.05393	0.21665	0.13773
22	1.30024	0.05677	0.26758	0.15559
24	1.37714	0.05975	0.32445	0.17390
26	1.45838	0.06290	0.38739	0.19265
28	1.54420	0.06620	0.45650	0.21180
30	1.63490	0.06968	0.53187	0.23134
32	1.73077	0.07335	0.61361	0.25125
34	1.83210	0.07720	0.70180	0.27150
36	1.93922	0.08126	0.79652	0.29209
38	2.05247	0.08553	0.89785	0.31301
40	2.17220	0.09003	1.00588	0.33423
42	2.29880	0.09476	1.12068	0.35575
44	2.43265	0.09975	1.24231	0.37756
46	2.57418	0.10499	1.37086	0.39965
48	2.72384	0.11051	1.50638	0.42201
50	2.88209	0.11632	1.64893	0.44462
52	3.04943	0.12244	1.79859	0.46750
54	3.22639	0.12887	1.95540	0.49062
56	3.41351	0.13565	2.11944	0.51398
58	3.61138	0.14278	2.29075	0.53757
60	3.82063	0.15029	2.46938	0.56139
62	4.04192	0.15819	2.65541	0.58544
64	4.27591	0.16651	2.84887	0.60970
66	4.52337	0.17526	3.04982	0.63417
68	4.78504	0.18448	3.25830	0.65886
70	5.06177	0.19417	3.47437	0.68374
72	5.35440	0.20438	3.69807	0.70883
74	5.66386	0.21513	3.92945	0.73411
76	5.99111	0.22644	4.16856	0.75958
78	6.33716	0.23834	4.41544	0.78524
80	6.70312	0.25088	4.67013	0.81108

Table 51. Fuel, tires, oil and maintenance in gallons, .001 inches, quarts and dollars respectively per vehicle hour for tangent sections with +2% grade

VEHICLE OPERATION PARAMETERS

SPEED	FUEL	OIL	TIRES	MAINT
2	0.74443	0.03348	0.00144	0.00735
4	0.81069	0.03534	0.00660	0.01785
6	0.87205	0.03731	0.01611	0.03000
8	0.93333	0.03938	0.03034	0.04336
10	0.99616	0.04157	0.04957	0.05769
12	1.06136	0.04388	0.07404	0.07285
14	1.12947	0.04632	0.10393	0.08874
16	1.20089	0.04889	0.13941	0.10528
18	1.27597	0.05161	0.18065	0.12242
20	1.35502	0.05448	0.22778	0.14009
22	1.43835	0.05750	0.28091	0.15827
24	1.52626	0.06070	0.34018	0.17691
26	1.61906	0.06407	0.40568	0.19600
28	1.71707	0.06763	0.47752	0.21550
30	1.82061	0.07139	0.55579	0.23540
32	1.93002	0.07536	0.64058	0.25567
34	2.04567	0.07954	0.73197	0.27630
36	2.16793	0.08396	0.83006	0.29728
38	2.29719	0.08863	0.93490	0.31858
40	2.43387	0.09356	1.04658	0.34020
42	2.57841	0.09875	1.16517	0.36212
44	2.73126	0.10424	1.29074	0.38434
46	2.89291	0.11003	1.42334	0.40684
48	3.06389	0.11615	1.56305	0.42962
50	3.24473	0.12260	1.70992	0.45266
52	3.43601	0.12942	1.86401	0.47597
54	3.63834	0.13661	2.02539	0.49952
56	3.85234	0.14420	2.19409	0.52333
58	4.07872	0.15221	2.37019	0.54737
60	4.31819	0.16067	2.55373	0.57164
62	4.57149	0.16960	2.74475	0.59615
64	4.83944	0.17902	2.94332	0.62087
66	5.12287	0.18897	3.14948	0.64581
68	5.42269	0.19947	3.36326	0.67097
70	5.73985	0.21056	3.58473	0.69633
72	6.07535	0.22226	3.81393	0.72190
74	6.43024	0.23461	4.05090	0.74767
76	6.80566	0.24764	4.29568	0.77363
78	7.20276	0.26141	4.54830	0.79978
80	7.62284	0.27593	4.80883	0.82613

Table 52. Fuel, tires, oil and maintenance
in gallons, .001 inches, quarts and
dollars respectively per vehicle hour
for tangent sections with +3% grade

VEHICLE OPERATION PARAMETERS

SPEED	FUEL	OIL	TIRES	MAINT
2	0.78231	0.03297	0.00156	0.00746
4	0.86468	0.03490	0.00711	0.01813
6	0.93822	0.03694	0.01725	0.03048
8	1.01035	0.03910	0.03234	0.04406
10	1.08353	0.04139	0.05266	0.05864
12	1.15897	0.04382	0.07844	0.07406
14	1.23742	0.04639	0.10985	0.09023
16	1.31943	0.04910	0.14706	0.10707
18	1.40546	0.05198	0.19023	0.12450
20	1.49590	0.05502	0.23947	0.14249
22	1.59113	0.05825	0.29491	0.16100
24	1.69152	0.06166	0.35667	0.17998
26	1.79745	0.06527	0.42483	0.19941
28	1.90928	0.06909	0.49951	0.21927
30	2.02740	0.07314	0.58078	0.23953
32	2.15222	0.07742	0.66873	0.26018
34	2.28414	0.08196	0.76345	0.28119
36	2.42362	0.08676	0.86501	0.30255
38	2.57109	0.09184	0.97348	0.32425
40	2.72706	0.09722	1.08893	0.34627
42	2.89202	0.10291	1.21144	0.36860
44	3.06652	0.10894	1.34105	0.39123
46	3.25111	0.11532	1.47784	0.41416
48	3.44640	0.12207	1.62186	0.43736
50	3.65300	0.12923	1.77317	0.46084
52	3.87160	0.13679	1.93182	0.48459
54	4.10289	0.14481	2.09789	0.50859
56	4.34761	0.15329	2.27139	0.53284
58	4.60654	0.16227	2.45240	0.55734
60	4.88053	0.17177	2.64095	0.58208
62	5.17045	0.18183	2.83711	0.60705
64	5.47722	0.19248	3.04092	0.63225
66	5.80183	0.20375	3.25240	0.65767
68	6.14531	0.21569	3.47162	0.68331
70	6.50877	0.22832	3.69862	0.70916
72	6.89337	0.24169	3.93343	0.73521
74	7.30032	0.25585	4.17611	0.76148
76	7.73095	0.27084	4.42668	0.78794
78	8.18659	0.28670	4.68519	0.81460
80	8.66875	0.30349	4.95168	0.84145

Table 53. Fuel, tires, oil and maintenance in gallons, .001 inches, quarts and dollars respectively per vehicle hour for tangent sections with +4% grade

VEHICLE OPERATION PARAMETERS SPEED	FUEL	OIL	TIRES	MAINT
2	0.82212	0.03246	0.00170	0.00757
4	0.92226	0.03446	0.00766	0.01841
6	1.00942	0.03658	0.01846	0.03096
8	1.09374	0.03883	0.03447	0.04477
10	1.17857	0.04122	0.05594	0.05960
12	1.26555	0.04376	0.08310	0.07529
14	1.35568	0.04645	0.11611	0.09175
16	1.44967	0.04932	0.15513	0.10888
18	1.54808	0.05235	0.20031	0.12662
20	1.65142	0.05558	0.25176	0.14493
22	1.76014	0.05900	0.30961	0.16377
24	1.87469	0.06263	0.37395	0.18310
26	1.99549	0.06649	0.44489	0.20288
28	2.12301	0.07058	0.52251	0.22310
30	2.25769	0.07493	0.60689	0.24374
32	2.39999	0.07954	0.69813	0.26476
34	2.55042	0.08444	0.79628	0.28616
36	2.70946	0.08964	0.90144	0.30792
38	2.87766	0.09516	1.01365	0.33002
40	3.05557	0.10102	1.13299	0.35245
42	3.24379	0.10724	1.25953	0.37520
44	3.44294	0.11385	1.39332	0.39825
46	3.65366	0.12086	1.53441	0.42161
48	3.87666	0.12830	1.68287	0.44525
50	4.11265	0.13620	1.83875	0.46917
52	4.36241	0.14459	2.00209	0.49336
54	4.62675	0.15350	2.17296	0.51782
56	4.90653	0.16295	2.35140	0.54254
58	5.20267	0.17298	2.53745	0.56750
60	5.51611	0.18364	2.73115	0.59271
62	5.84789	0.19494	2.93256	0.61816
64	6.19907	0.20695	3.14173	0.64384
66	6.57078	0.21969	3.35867	0.66974
68	6.96423	0.23322	3.58345	0.69587
70	7.38070	0.24759	3.81610	0.72222
72	7.82153	0.26283	4.05666	0.74878
74	8.28814	0.27902	4.30517	0.77554
76	8.78204	0.29620	4.56166	0.80252
78	9.30481	0.31444	4.82617	0.82969
80	9.85816	0.33380	5.09874	0.85706

Table 54. Fuel, tires, oil and maintenance in gallons, .001 inches, quarts and dollars respectively per vehicle hour for tangent sections with +5% grade

VEHICLE OPERATION PARAMETERS

SPEED	FUEL	OIL	TIRES	MAINT
2	0.86396	0.03196	0.00185	0.00768
4	0.98367	0.03402	0.00825	0.01870
6	1.08602	0.03622	0.01977	0.03146
8	1.18400	0.03856	0.03674	0.04550
10	1.28194	0.04105	0.05943	0.06058
12	1.38194	0.04370	0.08803	0.07655
14	1.48524	0.04652	0.12272	0.09329
16	1.59276	0.04953	0.16364	0.11072
18	1.70518	0.05273	0.21092	0.12878
20	1.82311	0.05613	0.26469	0.14742
22	1.94710	0.05976	0.32504	0.16659
24	2.07768	0.06362	0.39208	0.18627
26	2.21536	0.06773	0.46589	0.20642
28	2.36067	0.07211	0.54656	0.22700
30	2.51413	0.07677	0.63418	0.24801
32	2.67629	0.08172	0.72881	0.26943
34	2.84772	0.08700	0.83053	0.29122
36	3.02901	0.09262	0.93939	0.31338
38	3.22077	0.09861	1.05548	0.33589
40	3.42366	0.10498	1.17884	0.35874
42	3.63835	0.11176	1.30954	0.38191
44	3.86556	0.11898	1.44762	0.40540
46	4.10606	0.12667	1.59316	0.42919
48	4.36063	0.13485	1.74618	0.45328
50	4.63013	0.14356	1.90676	0.47765
52	4.91544	0.15283	2.07492	0.50230
54	5.21750	0.16271	2.25073	0.52722
56	5.53732	0.17322	2.43422	0.55240
58	5.87593	0.18441	2.62544	0.57784
60	6.23446	0.19632	2.82443	0.60353
62	6.61408	0.20900	3.03123	0.62946
64	7.01603	0.22251	3.24588	0.65563
66	7.44164	0.23688	3.46843	0.68203
68	7.89228	0.25218	3.69889	0.70866
70	8.36944	0.26847	3.93733	0.73552
72	8.87467	0.28582	4.18375	0.76259
74	9.40962	0.30428	4.43823	0.78987
76	9.97605	0.32394	4.70077	0.81736
78	10.57577	0.34487	4.97141	0.84506
80	11.21077	0.36714	5.25018	0.87296

Table 55. Fuel, tires, oil and maintenance in gallons, .001 inches, quarts and dollars respectively per vehicle hour for tangent sections with +6% grade

VEHICLE OPERATION PARAMETERS

SPEED	FUEL	OIL	TIRES	MAINT
2	0.90792	0.03146	0.00202	0.00780
4	1.04917	0.03359	0.00889	0.01899
6	1.16843	0.03586	0.02116	0.03196
8	1.28172	0.03829	0.03916	0.04624
10	1.39438	0.04088	0.06314	0.06158
12	1.50902	0.04364	0.09327	0.07782
14	1.62719	0.04659	0.12971	0.09485
16	1.74997	0.04974	0.17262	0.11259
18	1.87822	0.05311	0.22210	0.13097
20	2.01265	0.05670	0.27828	0.14995
22	2.15392	0.06053	0.34124	0.16947
24	2.30265	0.06463	0.41108	0.18950
26	2.45945	0.06900	0.48789	0.21001
28	2.62493	0.07366	0.57173	0.23097
30	2.79970	0.07865	0.66270	0.25237
32	2.98440	0.08396	0.76084	0.27417
34	3.17969	0.08964	0.86624	0.29637
36	3.38625	0.09571	0.97895	0.31894
38	3.60479	0.10218	1.09903	0.34186
40	3.83608	0.10909	1.22654	0.36514
42	4.08089	0.11647	1.36153	0.38874
44	4.34006	0.12434	1.50405	0.41267
46	4.61446	0.13275	1.65415	0.43691
48	4.90503	0.14173	1.81188	0.46145
50	5.21272	0.15131	1.97729	0.48628
52	5.53858	0.16155	2.15041	0.51140
54	5.88369	0.17247	2.33129	0.53679
56	6.24920	0.18414	2.51998	0.56245
58	6.63632	0.19659	2.71651	0.58837
60	7.04636	0.20988	2.92091	0.61455
62	7.48066	0.22408	3.13323	0.64098
64	7.94068	0.23923	3.35351	0.66765
66	8.42792	0.25541	3.58178	0.69455
68	8.94399	0.27268	3.81806	0.72169
70	9.49062	0.29113	4.06242	0.74906
72	10.06961	0.31081	4.31485	0.77665
74	10.68285	0.33183	4.57541	0.80446
76	11.33239	0.35428	4.84413	0.83248
78	12.02032	0.37823	5.12102	0.86072
80	12.74897	0.40381	5.40614	0.88916

Table 56. Fuel, tires, oil and maintenance in gallons, .001 inches, quarts and dollars respectively per vehicle hour for tangent sections with -1% grade

VEHICLE OPERATION PARAMETERS

SPEED	FUEL	OIL	TIRES	MAINT
2	0.55249	0.03401	0.00141	0.00729
4	0.49751	0.03580	0.00631	0.01754
6	0.45249	0.03768	0.01515	0.02932
8	0.41494	0.03966	0.02820	0.04222
10	0.38314	0.04174	0.04567	0.05602
12	0.40392	0.04394	0.06770	0.07057
14	0.43115	0.04625	0.09445	0.08579
16	0.46430	0.04868	0.12603	0.10161
18	0.50305	0.05124	0.16254	0.11796
20	0.54716	0.05393	0.20408	0.13481
22	0.59651	0.05677	0.25074	0.15211
24	0.65107	0.05975	0.30258	0.16984
26	0.71084	0.06290	0.35969	0.18797
28	0.77588	0.06620	0.42213	0.20647
30	0.84630	0.06968	0.48997	0.22533
32	0.92225	0.07335	0.56326	0.24453
34	1.00390	0.07720	0.64207	0.26405
36	1.09147	0.08126	0.72644	0.28389
38	1.18519	0.08553	0.81643	0.30401
40	1.28533	0.09003	0.91208	0.32443
42	1.39218	0.09476	1.01345	0.34512
44	1.50607	0.09975	1.12058	0.36607
46	1.62734	0.10499	1.23351	0.38728
48	1.75637	0.11051	1.35228	0.40873
50	1.89358	0.11632	1.47693	0.43043
52	2.03938	0.12244	1.60750	0.45236
54	2.19425	0.12887	1.74403	0.47452
56	2.35869	0.13565	1.88656	0.49689
58	2.53321	0.14278	2.03512	0.51948
60	2.71838	0.15029	2.18973	0.54228
62	2.91481	0.15819	2.35045	0.56529
64	3.12313	0.16651	2.51729	0.58849
66	3.34401	0.17526	2.69029	0.61189
68	3.57817	0.18448	2.86948	0.63547
70	3.82636	0.19417	3.05490	0.65925
72	4.08940	0.20438	3.24655	0.68320
74	4.36814	0.21513	3.44449	0.70733
76	4.66349	0.22644	3.64873	0.73164
78	4.97641	0.23834	3.85930	0.75612
80	5.30792	0.25088	4.07623	0.78077

Table 57. Fuel, tires, oil and maintenance in gallons, .001 inches, quarts and dollars respectively per vehicle hour for tangent sections with -2% grade

VEHICLE OPERATION PARAMETERS

SPEED	FUEL	OIL	TIRES	MAINT
2	0.55249	0.03348	0.00164	0.00744
4	0.49751	0.03534	0.00699	0.01778
6	0.45249	0.03731	0.01632	0.02958
8	0.41494	0.03938	0.02978	0.04246
10	0.38314	0.04157	0.04747	0.05619
12	0.35587	0.04388	0.06949	0.07065
14	0.33223	0.04632	0.09591	0.08575
16	0.31153	0.04889	0.12678	0.10141
18	0.32217	0.05161	0.16217	0.11757
20	0.36628	0.05448	0.20211	0.13421
22	0.41563	0.05750	0.24667	0.15128
24	0.47019	0.06070	0.29586	0.16875
26	0.52996	0.06407	0.34973	0.18659
28	0.59500	0.06763	0.40832	0.20479
30	0.66542	0.07139	0.47166	0.22333
32	0.74137	0.07536	0.53977	0.24219
34	0.82303	0.07954	0.61268	0.26135
36	0.91059	0.08396	0.69043	0.28080
38	1.00431	0.08863	0.77302	0.30053
40	1.10445	0.09356	0.86050	0.32053
42	1.21130	0.09875	0.95287	0.34079
44	1.32519	0.10424	1.05017	0.36130
46	1.44646	0.11003	1.15241	0.38204
48	1.57550	0.11615	1.25962	0.40302
50	1.71270	0.12260	1.37180	0.42422
52	1.85851	0.12942	1.48899	0.44564
54	2.01337	0.13661	1.61119	0.46727
56	2.17781	0.14420	1.73843	0.48911
58	2.35233	0.15221	1.87072	0.51115
60	2.53751	0.16067	2.00807	0.53339
62	2.73394	0.16960	2.15052	0.55581
64	2.94225	0.17902	2.29805	0.57843
66	3.16313	0.18897	2.45070	0.60122
68	3.39729	0.19947	2.60848	0.62419
70	3.64548	0.21056	2.77140	0.64733
72	3.90852	0.22226	2.93947	0.67065
74	4.18727	0.23461	3.11270	0.69413
76	4.48262	0.24764	3.29113	0.71777
78	4.79554	0.26141	3.47473	0.74158
80	5.12704	0.27593	3.66355	0.76554

Table 58. Fuel, tires, oil and maintenance in gallons, .001 inches, quarts and dollars respectively per vehicle hour for tangent sections with -3% grade

VEHICLE OPERATION PARAMETERS

SPEED	FUEL	OIL	TIRES	MAINT
2	0.55249	0.03297	0.00191	0.00760
4	0.49751	0.03490	0.00775	0.01801
6	0.45249	0.03694	0.01759	0.02984
8	0.41494	0.03910	0.03144	0.04270
10	0.38314	0.04139	0.04935	0.05637
12	0.35587	0.04382	0.07133	0.07074
14	0.33223	0.04639	0.09738	0.08570
16	0.31153	0.04910	0.12753	0.10120
18	0.29326	0.05198	0.16179	0.11719
20	0.27701	0.05502	0.20016	0.13361
22	0.26247	0.05825	0.24266	0.15045
24	0.24938	0.06166	0.28929	0.16766
26	0.30914	0.06527	0.34006	0.18523
28	0.37419	0.06909	0.39497	0.20313
30	0.44461	0.07314	0.45403	0.22135
32	0.52056	0.07742	0.51726	0.23987
34	0.60221	0.08196	0.58464	0.25868
36	0.68978	0.08676	0.65620	0.27775
38	0.78350	0.09184	0.73192	0.29709
40	0.88364	0.09722	0.81183	0.31669
42	0.99049	0.10291	0.89591	0.33652
44	1.10438	0.10894	0.98419	0.35658
46	1.22565	0.11532	1.07665	0.37687
48	1.35468	0.12207	1.17330	0.39738
50	1.49189	0.12923	1.27416	0.41810
52	1.63769	0.13679	1.37921	0.43902
54	1.79256	0.14481	1.48847	0.46014
56	1.95699	0.15329	1.60193	0.48146
58	2.13152	0.16227	1.71960	0.50296
60	2.31669	0.17177	1.84149	0.52464
62	2.51312	0.18183	1.96759	0.54650
64	2.72144	0.19248	2.09791	0.56854
66	2.94232	0.20375	2.23245	0.59074
68	3.17648	0.21569	2.37122	0.61311
70	3.42467	0.22832	2.51421	0.63564
72	3.68771	0.24169	2.66143	0.65833
74	3.96645	0.25585	2.81288	0.68117
76	4.26180	0.27084	2.96857	0.70417
78	4.57472	0.28670	3.12849	0.72731
80	4.90623	0.30349	3.29265	0.75060

Table 59. Fuel, tires, oil and maintenance in gallons, .001 inches, quarts and dollars respectively per vehicle hour for tangent sections with -4% grade

VEHICLE OPERATION PARAMETERS

SPEED	FUEL	OIL	TIRES	MAINT
2	0.55249	0.03246	0.00222	0.00776
4	0.49751	0.03446	0.00859	0.01826
6	0.45249	0.03658	0.01895	0.03011
8	0.41494	0.03883	0.03320	0.04294
10	0.38314	0.04122	0.05131	0.05655
12	0.35587	0.04376	0.07321	0.07082
14	0.33223	0.04645	0.09888	0.08566
16	0.31153	0.04932	0.12829	0.10100
18	0.29326	0.05235	0.16141	0.11680
20	0.27701	0.05558	0.19823	0.13302
22	0.26247	0.05900	0.23872	0.14962
24	0.24938	0.06263	0.28286	0.16658
26	0.23753	0.06649	0.33064	0.18387
28	0.22676	0.07058	0.38205	0.20148
30	0.21692	0.07493	0.43707	0.21939
32	0.25099	0.07954	0.49568	0.23757
34	0.33264	0.08444	0.55789	0.25603
36	0.42021	0.08964	0.62367	0.27474
38	0.51393	0.09516	0.69301	0.29369
40	0.61407	0.10102	0.76591	0.31288
42	0.72092	0.10724	0.84236	0.33230
44	0.83481	0.11385	0.92235	0.35193
46	0.95608	0.12086	1.00586	0.37178
48	1.08512	0.12830	1.09290	0.39182
50	1.22232	0.13620	1.18346	0.41207
52	1.36812	0.14459	1.27752	0.43250
54	1.52299	0.15350	1.37508	0.45312
56	1.68743	0.16295	1.47614	0.47392
58	1.86195	0.17298	1.58069	0.49489
60	2.04713	0.18364	1.68871	0.51603
62	2.24355	0.19494	1.80022	0.53734
64	2.45187	0.20695	1.91519	0.55881
66	2.67275	0.21969	2.03363	0.58044
68	2.90691	0.23322	2.15553	0.60222
70	3.15510	0.24759	2.28088	0.62415
72	3.41814	0.26283	2.40968	0.64623
74	3.69689	0.27902	2.54192	0.66845
76	3.99223	0.29620	2.67761	0.69082
78	4.30515	0.31444	2.81673	0.71332
80	4.63666	0.33380	2.95928	0.73596

Table 60. Fuel, tires, oil and maintenance in gallons, .001 inches, quarts and dollars respectively per vehicle hour for tangent sections with -5% grade

VEHICLE OPERATION PARAMETERS

SPEED	FUEL	OIL	TIRES	MAINT
2	0.55249	0.03196	0.00259	0.00792
4	0.49751	0.03402	0.00953	0.01850
6	0.45249	0.03622	0.02041	0.03037
8	0.41494	0.03856	0.03506	0.04318
10	0.38314	0.04105	0.05334	0.05673
12	0.35587	0.04370	0.07514	0.07090
14	0.33223	0.04652	0.10040	0.08561
16	0.31153	0.04953	0.12905	0.10080
18	0.29326	0.05273	0.16104	0.11642
20	0.27701	0.05613	0.19632	0.13243
22	0.26247	0.05976	0.23484	0.14880
24	0.24938	0.06362	0.27658	0.16551
26	0.23753	0.06773	0.32149	0.18253
28	0.22676	0.07211	0.36955	0.19984
30	0.21692	0.07677	0.42074	0.21744
32	0.20790	0.08172	0.47501	0.23530
34	0.19960	0.08700	0.53236	0.25341
36	0.19194	0.09262	0.59275	0.27175
38	0.18484	0.09861	0.65617	0.29033
40	0.28498	0.10498	0.72259	0.30913
42	0.39183	0.11176	0.79201	0.32813
44	0.50572	0.11898	0.86439	0.34734
46	0.62700	0.12667	0.93973	0.36675
48	0.75603	0.13485	1.01801	0.38635
50	0.89323	0.14356	1.09922	0.40612
52	1.03904	0.15283	1.18333	0.42608
54	1.19391	0.16271	1.27034	0.44621
56	1.35834	0.17322	1.36024	0.46650
58	1.53287	0.18441	1.45300	0.48696
60	1.71804	0.19632	1.54862	0.50757
62	1.91447	0.20900	1.64709	0.52834
64	2.12278	0.22251	1.74839	0.54926
66	2.34366	0.23688	1.85252	0.57032
68	2.57782	0.25218	1.95946	0.59153
70	2.82601	0.26847	2.06921	0.61288
72	3.08906	0.28582	2.18175	0.63436
74	3.36760	0.30428	2.29708	0.65598
76	3.66315	0.32394	2.41518	0.67773
78	3.97607	0.34487	2.53605	0.69960
80	4.30757	0.36714	2.65968	0.72160

Table 61. Fuel, tires, oil and maintenance in gallons, .001 inches, quarts and dollars respectively per vehicle hour for tangent sections with -6% grade

VEHICLE OPERATION PARAMETERS

SPEED	FUEL	OIL	TIRES	MAINT
2	0.55249	0.03146	0.00301	0.00809
4	0.49751	0.03359	0.01056	0.01875
6	0.45249	0.03586	0.02200	0.03064
8	0.41494	0.03829	0.03702	0.04343
10	0.38314	0.04088	0.05545	0.05691
12	0.35587	0.04364	0.07713	0.07098
14	0.33223	0.04659	0.10195	0.08557
16	0.31153	0.04974	0.12982	0.10060
18	0.29326	0.05311	0.16067	0.11603
20	0.27701	0.05670	0.19442	0.13184
22	0.26247	0.06053	0.23103	0.14798
24	0.24938	0.06463	0.27043	0.16444
26	0.23753	0.06900	0.31259	0.18119
28	0.22676	0.07366	0.35747	0.19822
30	0.21692	0.07865	0.40501	0.21551
32	0.20790	0.08396	0.45520	0.23304
34	0.19960	0.08964	0.50799	0.25081
36	0.19194	0.09571	0.56336	0.26880
38	0.18484	0.10218	0.62128	0.28701
40	0.17825	0.10909	0.68172	0.30542
42	0.17212	0.11647	0.74466	0.32402
44	0.16639	0.12434	0.81008	0.34282
46	0.22525	0.13275	0.87795	0.36179
48	0.35428	0.14173	0.94826	0.38094
50	0.49149	0.15131	1.02098	0.40026
52	0.63729	0.16155	1.09609	0.41975
54	0.79216	0.17247	1.17358	0.43940
56	0.95659	0.18414	1.25343	0.45920
58	1.13112	0.19659	1.33562	0.47915
60	1.31629	0.20988	1.42015	0.49925
62	1.51272	0.22408	1.50699	0.51949
64	1.72104	0.23923	1.59612	0.53987
66	1.94192	0.25541	1.68754	0.56038
68	2.17607	0.27268	1.78123	0.58103
70	2.42427	0.29113	1.87719	0.60180
72	2.68731	0.31081	1.97538	0.62271
74	2.96605	0.33183	2.07582	0.64373
76	3.26140	0.35428	2.17848	0.66488
78	3.57432	0.37823	2.28334	0.68614
80	3.90582	0.40381	2.39041	0.70752

Table 62. Fuel, tires, oil and maintenance in gallons, .001 inches, quarts and dollars respectively per vehicle hour for level sections with 1° curvature

VEHICLE OPERATION PARAMETERS

SPEED	FUEL	OIL	TIRES	MAINT
2	0.65463	0.03454	0.05279	0.00714
4	0.69464	0.03625	0.06187	0.01731
6	0.73709	0.03805	0.07250	0.02907
8	0.78213	0.03994	0.08496	0.04198
10	0.82993	0.04192	0.09956	0.05584
12	0.88065	0.04400	0.11667	0.07049
14	0.93447	0.04618	0.13672	0.08584
16	0.99158	0.04847	0.16022	0.10181
18	1.05217	0.05087	0.18776	0.11835
20	1.11647	0.05340	0.22003	0.13541
22	1.18470	0.05605	0.25784	0.15295
24	1.25710	0.05882	0.30216	0.17094
26	1.33393	0.06174	0.35409	0.18935
28	1.41545	0.06480	0.41495	0.20816
30	1.50195	0.06802	0.48626	0.22735
32	1.59373	0.07139	0.56984	0.24690
34	1.69113	0.07493	0.66778	0.26679
36	1.79448	0.07865	0.78255	0.28700
38	1.90414	0.08255	0.91704	0.30754
40	2.02051	0.08664	1.07465	0.32837
42	2.14398	0.09094	1.25935	0.34950
44	2.27501	0.09545	1.47580	0.37091
46	2.41404	0.10018	1.72944	0.39259
48	2.56156	0.10515	2.02668	0.41453
50	2.71811	0.11036	2.37500	0.43673
52	2.88421	0.11583	2.78319	0.45918
54	3.06047	0.12158	3.26153	0.48187
56	3.24751	0.12761	3.82209	0.50480
58	3.44597	0.13394	4.47898	0.52795
60	3.65656	0.14058	5.24878	0.55133
62	3.88002	0.14755	6.15088	0.57492
64	4.11713	0.15487	7.20803	0.59873
66	4.36874	0.16254	8.44687	0.62274
68	4.63572	0.17061	9.89862	0.64696
70	4.91902	0.17907	11.59989	0.67138
72	5.21963	0.18795	13.59355	0.69599
74	5.53862	0.19727	15.92986	0.72079
76	5.87709	0.20705	18.66769	0.74578
78	6.23625	0.21732	21.87608	0.77095
80	6.61736	0.22809	25.63591	0.79631

Table 63. Fuel, tires, oil and maintenance in gallons, .001 inches, quarts and dollars respectively per vehicle hour for level sections with 2° curvature

VEHICLE OPERATION PARAMETERS

SPEED	FUEL	OIL	TIRES	MAINT
2	0.65220	0.03454	0.07983	0.00714
4	0.69046	0.03625	0.09398	0.01731
6	0.73096	0.03805	0.11064	0.02907
8	0.77383	0.03994	0.13026	0.04198
10	0.81922	0.04192	0.15335	0.05584
12	0.86727	0.04400	0.18053	0.07049
14	0.91814	0.04618	0.21254	0.08584
16	0.97200	0.04847	0.25021	0.10181
18	1.02901	0.05087	0.29457	0.11835
20	1.08937	0.05340	0.34679	0.13541
22	1.15327	0.05605	0.40826	0.15295
24	1.22204	0.05882	0.48064	0.17094
26	1.30019	0.06174	0.56584	0.18935
28	1.38333	0.06480	0.66615	0.20816
30	1.47179	0.06802	0.78424	0.22735
32	1.56591	0.07139	0.92326	0.24690
34	1.66604	0.07493	1.08693	0.26679
36	1.77258	0.07865	1.27961	0.28700
38	1.88593	0.08255	1.50645	0.30754
40	2.00654	0.08664	1.77350	0.32837
42	2.13485	0.09094	2.08789	0.34950
44	2.27136	0.09545	2.45802	0.37091
46	2.41661	0.10018	2.89376	0.39259
48	2.57115	0.10515	3.40674	0.41453
50	2.73556	0.11036	4.01066	0.43673
52	2.91049	0.11583	4.72164	0.45918
54	3.09661	0.12158	5.55865	0.48187
56	3.29463	0.12761	6.54404	0.50480
58	3.50531	0.13394	7.70411	0.52795
60	3.72947	0.14058	9.06984	0.55133
62	3.96795	0.14755	10.67767	0.57492
64	4.22169	0.15487	12.57053	0.59873
66	4.49166	0.16254	14.79892	0.62274
68	4.77889	0.17061	17.42235	0.64696
70	5.08449	0.17907	20.51083	0.67138
72	5.40962	0.18795	24.14685	0.69599
74	5.75556	0.19727	28.42740	0.72079
76	6.12360	0.20705	33.46680	0.74578
78	6.51519	0.21732	39.39951	0.77095
80	6.93182	0.22809	46.38396	0.79631

Table 64. Fuel, tires, oil and maintenance in gallons, .001 inches, quarts and dollars respectively per vehicle hour for level sections with 3° curvature

VEHICLE OPERATION PARAMETERS

SPEED	FUEL	OIL	TIRES	MAINT
2	0.65220	0.03454	0.10187	0.00714
4	0.69046	0.03625	0.12049	0.01731
6	0.73096	0.03805	0.14250	0.02907
8	0.77383	0.03994	0.16853	0.04198
10	0.81922	0.04192	0.19932	0.05584
12	0.86727	0.04400	0.23574	0.07049
14	0.91814	0.04618	0.27881	0.08584
16	0.97200	0.04847	0.32975	0.10181
18	1.02901	0.05087	0.39000	0.11835
20	1.08937	0.05340	0.46125	0.13541
22	1.15327	0.05605	0.54552	0.15295
24	1.22091	0.05882	0.64518	0.17094
26	1.30145	0.06174	0.76306	0.18935
28	1.38854	0.06480	0.90247	0.20816
30	1.48146	0.06802	1.06735	0.22735
32	1.58060	0.07139	1.26235	0.24690
34	1.68637	0.07493	1.49298	0.26679
36	1.79921	0.07865	1.76575	0.28700
38	1.91961	0.08255	2.08836	0.30754
40	2.04807	0.08664	2.46990	0.32837
42	2.18512	0.09094	2.92115	0.34950
44	2.33135	0.09545	3.45484	0.37091
46	2.48736	0.10018	4.08605	0.39259
48	2.65380	0.10515	4.83257	0.41453
50	2.83139	0.11036	5.71547	0.43673
52	3.02086	0.11583	6.75968	0.45918
54	3.22301	0.12158	7.99468	0.48187
56	3.43868	0.12761	9.45531	0.50480
58	3.66880	0.13394	11.18279	0.52795
60	3.91430	0.14058	13.22589	0.55133
62	4.17624	0.14755	15.64226	0.57492
64	4.45570	0.15487	18.50009	0.59873
66	4.75387	0.16254	21.88004	0.62274
68	5.07199	0.17061	25.87752	0.64696
70	5.41140	0.17907	30.60535	0.67138
72	5.77351	0.18795	36.19695	0.69599
74	6.15986	0.19727	42.81012	0.72079
76	6.57207	0.20705	50.63153	0.74578
78	7.01185	0.21732	59.88191	0.77095
80	7.48108	0.22809	70.82234	0.79631

Table 65. Fuel, tires, oil and maintenance in gallons, .001 inches, quarts and dollars respectively per vehicle hour for level sections with 4° curvature

VEHICLE OPERATION PARAMETERS

SPEED	FUEL	OIL	TIRES	MAINT
2	0.65220	0.03454	0.12128	0.00714
4	0.69046	0.03625	0.14409	0.01731
6	0.73096	0.03805	0.17121	0.02907
8	0.77383	0.03994	0.20342	0.04198
10	0.81922	0.04192	0.24169	0.05584
12	0.86727	0.04400	0.28717	0.07049
14	0.91814	0.04618	0.34120	0.08584
16	0.97200	0.04847	0.40540	0.10181
18	1.02901	0.05087	0.48167	0.11835
20	1.08937	0.05340	0.57230	0.13541
22	1.15327	0.05605	0.67998	0.15295
24	1.23201	0.05882	0.80792	0.17094
26	1.31828	0.06174	0.95994	0.18935
28	1.41061	0.06480	1.14055	0.20816
30	1.50939	0.06802	1.35515	0.22735
32	1.61510	0.07139	1.61013	0.24690
34	1.72820	0.07493	1.91307	0.26679
36	1.84923	0.07865	2.27302	0.28700
38	1.97873	0.08255	2.70070	0.30754
40	2.11731	0.08664	3.20885	0.32837
42	2.26558	0.09094	3.81260	0.34950
44	2.42424	0.09545	4.52995	0.37091
46	2.59402	0.10018	5.38228	0.39259
48	2.77568	0.10515	6.39497	0.41453
50	2.97006	0.11036	7.59820	0.43673
52	3.17805	0.11583	9.02782	0.45918
54	3.40062	0.12158	10.72643	0.48187
56	3.63877	0.12761	12.74464	0.50480
58	3.89359	0.13394	15.14257	0.52795
60	4.16627	0.14058	17.99168	0.55133
62	4.45804	0.14755	21.37688	0.57492
64	4.77024	0.15487	25.39900	0.59873
66	5.10430	0.16254	30.17790	0.62274
68	5.46176	0.17061	35.85594	0.64696
70	5.84425	0.17907	42.60237	0.67138
72	6.25353	0.18795	50.61812	0.69599
74	6.69147	0.19727	60.14203	0.72079
76	7.16008	0.20705	71.45798	0.74578
78	7.66152	0.21732	84.90297	0.77095
80	8.19805	0.22809	100.87776	0.79631

Table 66. Fuel, tires, oil and maintenance in gallons, .001 inches, quarts and dollars respectively per vehicle hour for level sections with 5° curvature

VEHICLE OPERATION PARAMETERS

SPEED	FUEL	OIL	TIRES	MAINT
2	0.65220	0.03454	0.13898	0.00714
4	0.69046	0.03625	0.16589	0.01731
6	0.73096	0.03805	0.19801	0.02907
8	0.77383	0.03994	0.23635	0.04198
10	0.81922	0.04192	0.28212	0.05584
12	0.86727	0.04400	0.33674	0.07049
14	0.91814	0.04618	0.40195	0.08584
16	0.97200	0.04847	0.47978	0.10181
18	1.02901	0.05087	0.57268	0.11835
20	1.08937	0.05340	0.68357	0.13541
22	1.16770	0.05605	0.81592	0.15295
24	1.25328	0.05882	0.97391	0.17094
26	1.34514	0.06174	1.16249	0.18935
28	1.44373	0.06480	1.38759	0.20816
30	1.54955	0.06802	1.65627	0.22735
32	1.66312	0.07139	1.97697	0.24690
34	1.78502	0.07493	2.35977	0.26679
36	1.91585	0.07865	2.81670	0.28700
38	2.05627	0.08255	3.36210	0.30754
40	2.20698	0.08664	4.01310	0.32837
42	2.36874	0.09094	4.79016	0.34950
44	2.54236	0.09545	5.71769	0.37091
46	2.72869	0.10018	6.82481	0.39259
48	2.92869	0.10515	8.14631	0.41453
50	3.14334	0.11036	9.72368	0.43673
52	3.37373	0.11583	11.60648	0.45918
54	3.62101	0.12158	13.85386	0.48187
56	3.88640	0.12761	16.53638	0.50480
58	4.17125	0.13394	19.73833	0.52795
60	4.47698	0.14058	23.56029	0.55133
62	4.80512	0.14755	28.12230	0.57492
64	5.15730	0.15487	33.56764	0.59873
66	5.53531	0.16254	40.06735	0.62274
68	5.94101	0.17061	47.82564	0.64696
70	6.37645	0.17907	57.08618	0.67138
72	6.84380	0.18795	68.13985	0.69599
74	7.34542	0.19727	81.33377	0.72079
76	7.88379	0.20705	97.08252	0.74578
78	8.46162	0.21732	115.88072	0.77095
80	9.08180	0.22809	138.31885	0.79631

Table 67. Fuel, tires, oil and maintenance in gallons, .001 inches, quarts and dollars respectively per vehicle hour for level sections with 6° curvature

VEHICLE OPERATION PARAMETERS

SPEED	FUEL	OIL	TIRES	MAINT
2	0.65220	0.03454	0.15548	0.00714
4	0.69046	0.03625	0.18644	0.01731
6	0.73096	0.03805	0.22356	0.02907
8	0.77383	0.03994	0.26808	0.04198
10	0.81922	0.04192	0.32147	0.05584
12	0.86727	0.04400	0.38548	0.07049
14	0.91814	0.04618	0.46224	0.08584
16	0.97200	0.04847	0.55429	0.10181
18	1.02901	0.05087	0.66467	0.11835
20	1.10546	0.05340	0.79703	0.13541
22	1.19026	0.05605	0.95574	0.15295
24	1.28157	0.05882	1.14607	0.17094
26	1.37989	0.06174	1.37429	0.18935
28	1.48574	0.06480	1.64795	0.20816
30	1.59972	0.06802	1.97612	0.22735
32	1.72244	0.07139	2.36963	0.24690
34	1.85457	0.07493	2.84151	0.26679
36	1.99685	0.07865	3.40735	0.28700
38	2.15004	0.08255	4.08587	0.30754
40	2.31497	0.08664	4.89951	0.32837
42	2.49257	0.09094	5.87517	0.34950
44	2.68378	0.09545	7.04511	0.37091
46	2.88967	0.10018	8.44804	0.39259
48	3.11135	0.10515	10.13034	0.41453
50	3.35003	0.11036	12.14763	0.43673
52	3.60702	0.11583	14.56664	0.45918
54	3.88373	0.12158	17.46733	0.48187
56	4.18167	0.12761	20.94569	0.50480
58	4.50247	0.13394	25.11670	0.52795
60	4.84787	0.14058	30.11829	0.55133
62	5.21977	0.14755	36.11588	0.57492
64	5.62020	0.15487	43.30782	0.59873
66	6.05135	0.16254	51.93187	0.62274
68	6.51558	0.17061	62.27328	0.64696
70	7.01542	0.17907	74.67401	0.67138
72	7.55360	0.18795	89.54424	0.69599
74	8.13307	0.19727	107.37553	0.72079
76	8.75700	0.20705	128.75764	0.74578
78	9.42878	0.21732	154.39767	0.77095
80	10.15211	0.22809	185.14369	0.79631

APPENDIX C

The average benefit realized by a motorist for a time savings or the value of motorists time is a function of his trip purpose, income, and the amount of time saved. The average benefits generated by the program "value of time" algorithm are shown in Tables 68 through 72 for five passenger car trip purposes--work, social-recreational, personal business, vacation and school trips. The benefits are shown in dollars for eight income ranges by the amount of time saved in minutes.

The benefits for work and school trips are in dollars per person while the benefits for the other trip purposes are in dollars per vehicle. The reason for this is that school and work trips are considered to have occupants with a range of incomes while personal business, social-recreational, and vacation trips are classified as family trips where one annual income covers all vehicle occupants.

Table 68. Benefits of time savings for school trips in dollars per person

Time Saving (Minutes)	Income of Motorist (thousands of dollars per year) <4	4-6	6-8	8-10	10-12	12-15	15-20	>20
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
2	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001
3	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002
4	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.003
5	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.003
6	0.000	0.000	0.000	0.000	0.001	0.002	0.004	0.010
7	0.000	0.000	0.000	0.001	0.002	0.004	0.012	0.031
8	0.000	0.000	0.000	0.001	0.003	0.010	0.031	0.082
9	0.000	0.000	0.001	0.002	0.007	0.024	0.073	0.178
10	0.000	0.000	0.001	0.003	0.014	0.051	0.150	0.309
11	0.000	0.000	0.001	0.006	0.027	0.102	0.257	0.452
12	0.000	0.000	0.002	0.010	0.051	0.178	0.380	0.597
13	0.000	0.000	0.003	0.018	0.092	0.274	0.507	0.741
14	0.000	0.001	0.004	0.031	0.150	0.380	0.633	0.884
15	0.000	0.001	0.007	0.052	0.222	0.488	0.759	1.027
16	0.000	0.001	0.012	0.083	0.303	0.597	0.885	1.169
17	0.000	0.002	0.019	0.124	0.390	0.705	1.010	1.312
18	0.000	0.003	0.029	0.174	0.479	0.813	1.135	1.454
19	0.000	0.004	0.042	0.233	0.570	0.921	1.260	1.597
20	0.000	0.006	0.059	0.298	0.660	1.028	1.384	1.739
21	0.000	0.006	0.059	0.298	0.660	1.028	1.384	1.739
22	0.000	0.006	0.059	0.298	0.660	1.028	1.384	1.739
23	0.000	0.006	0.059	0.298	0.660	1.028	1.384	1.739
24	0.000	0.006	0.059	0.298	0.660	1.028	1.384	1.739
25	0.000	0.006	0.059	0.298	0.660	1.028	1.384	1.739
26	0.000	0.006	0.059	0.298	0.660	1.028	1.384	1.739
27	0.000	0.006	0.059	0.298	0.660	1.028	1.384	1.739
28	0.000	0.006	0.059	0.298	0.660	1.028	1.384	1.739
29	0.000	0.006	0.059	0.298	0.660	1.028	1.384	1.739
30	0.000	0.006	0.059	0.298	0.660	1.028	1.384	1.739
31	0.000	0.006	0.059	0.298	0.660	1.028	1.384	1.739
32	0.000	0.006	0.059	0.298	0.660	1.028	1.384	1.739
33	0.000	0.006	0.059	0.298	0.660	1.028	1.384	1.739
34	0.000	0.006	0.059	0.298	0.660	1.028	1.384	1.739
35	0.000	0.006	0.059	0.298	0.660	1.028	1.384	1.739
36	0.000	0.006	0.059	0.298	0.660	1.028	1.384	1.739
37	0.000	0.006	0.059	0.298	0.660	1.028	1.384	1.739
38	0.000	0.006	0.059	0.298	0.660	1.028	1.384	1.739
39	0.000	0.006	0.059	0.298	0.660	1.028	1.384	1.739
40	0.000	0.006	0.059	0.298	0.660	1.028	1.384	1.739

Table 69. Benefits of times savings for personal-business trips in dollars per vehicle

Time Saving (Minutes)	Income of Motorist (thousands of dollars per year) <4	4-6	6-8	8-10	10-12	12-15	15-20	>20
1	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.004
2	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.007
3	0.000	0.000	0.000	0.000	0.000	0.001	0.004	0.011
4	0.000	0.000	0.000	0.000	0.001	0.002	0.005	0.014
5	0.000	0.000	0.000	0.000	0.001	0.002	0.006	0.018
6	0.000	0.000	0.000	0.001	0.002	0.007	0.026	0.084
7	0.000	0.000	0.000	0.001	0.006	0.026	0.100	0.271
8	0.000	0.000	0.001	0.003	0.018	0.084	0.271	0.543
9	0.000	0.000	0.001	0.007	0.048	0.213	0.508	0.827
10	0.000	0.000	0.002	0.018	0.118	0.403	0.756	1.108
11	0.000	0.000	0.004	0.040	0.241	0.614	1.002	1.387
12	0.000	0.001	0.007	0.084	0.403	0.827	1.248	1.666
13	0.000	0.001	0.014	0.161	0.578	1.038	1.492	1.946
14	0.000	0.001	0.026	0.271	0.756	1.248	1.736	2.225
15	0.000	0.004	0.056	0.404	0.949	1.478	2.003	2.529
16	0.001	0.011	0.107	0.554	1.159	1.728	2.293	2.860
17	0.001	0.020	0.174	0.715	1.369	1.977	2.582	3.190
18	0.002	0.031	0.256	0.881	1.578	2.225	2.872	3.521
19	0.003	0.046	0.353	1.049	1.786	2.473	3.161	3.851
20	0.004	0.065	0.461	1.217	1.993	2.721	3.450	4.182
21	0.005	0.089	0.578	1.385	2.200	2.969	3.739	4.512
22	0.006	0.118	0.700	1.552	2.407	3.217	4.028	4.842
23	0.007	0.155	0.825	1.718	2.613	3.464	4.317	5.173
24	0.009	0.198	0.951	1.884	2.820	3.712	4.606	5.503
25	0.010	0.248	1.077	2.050	3.027	3.960	4.895	5.834
26	0.013	0.305	1.203	2.215	3.233	4.208	5.184	6.164
27	0.015	0.369	1.328	2.381	3.440	4.456	5.474	6.494
28	0.018	0.438	1.454	2.546	3.646	4.703	5.763	6.825
29	0.021	0.512	1.579	2.711	3.853	4.951	6.052	7.155
30	0.024	0.590	1.704	2.877	4.059	5.199	6.341	7.486
31	0.024	0.590	1.704	2.877	4.059	5.199	6.341	7.486
32	0.024	0.590	1.704	2.877	4.059	5.199	6.341	7.486
33	0.024	0.590	1.704	2.877	4.059	5.199	6.341	7.486
34	0.024	0.590	1.704	2.877	4.059	5.199	6.341	7.486
35	0.024	0.590	1.704	2.877	4.059	5.199	6.341	7.486
36	0.024	0.590	1.704	2.877	4.059	5.199	6.341	7.486
37	0.024	0.590	1.704	2.877	4.059	5.199	6.341	7.486
38	0.024	0.590	1.704	2.877	4.059	5.199	6.341	7.486
39	0.024	0.590	1.704	2.877	4.059	5.199	6.341	7.486
40	0.024	0.590	1.704	2.877	4.059	5.199	6.341	7.486

Table 70. Benefits of time savings for social-recreational trips in dollars per vehicle

Time Saving	Income of Motorist (Thousands of dollars per year)							
(Minutes)	<4	4-6	6-8	8-10	10-12	12-15	15-20	>20
1	0.000	0.000	0.000	0.001	0.001	0.002	0.005	0.010
2	0.000	0.000	0.001	0.001	0.002	0.005	0.010	0.020
3	0.000	0.000	0.001	0.002	0.004	0.007	0.015	0.030
4	0.000	0.001	0.001	0.002	0.005	0.010	0.020	0.040
5	0.000	0.001	0.001	0.003	0.006	0.012	0.025	0.049
6	0.000	0.001	0.002	0.005	0.012	0.029	0.064	0.131
7	0.000	0.001	0.003	0.009	0.025	0.064	0.145	0.277
8	0.000	0.002	0.005	0.016	0.049	0.131	0.277	0.466
9	0.001	0.002	0.008	0.029	0.093	0.235	0.441	0.669
10	0.001	0.003	0.012	0.049	0.161	0.368	0.618	0.872
11	0.001	0.004	0.019	0.082	0.255	0.516	0.796	1.073
12	0.001	0.005	0.029	0.131	0.368	0.669	0.973	1.274
13	0.001	0.007	0.043	0.196	0.491	0.821	1.148	1.474
14	0.001	0.009	0.064	0.277	0.618	0.973	1.324	1.674
15	0.002	0.014	0.087	0.344	0.719	1.097	1.469	1.839
16	0.003	0.020	0.109	0.392	0.795	1.196	1.585	1.971
17	0.005	0.027	0.132	0.444	0.874	1.295	1.701	2.103
18	0.006	0.035	0.158	0.497	0.954	1.394	1.817	2.234
19	0.007	0.043	0.185	0.554	1.035	1.494	1.932	2.365
20	0.009	0.052	0.214	0.612	1.117	1.593	2.047	2.496
21	0.009	0.052	0.214	0.612	1.117	1.593	2.047	2.496
22	0.009	0.052	0.214	0.612	1.117	1.593	2.047	2.496
23	0.009	0.052	0.214	0.612	1.117	1.593	2.047	2.496
24	0.009	0.052	0.214	0.612	1.117	1.593	2.047	2.496
25	0.009	0.052	0.214	0.612	1.117	1.593	2.047	2.496
26	0.009	0.052	0.214	0.612	1.117	1.593	2.047	2.496
27	0.009	0.052	0.214	0.612	1.117	1.593	2.047	2.496
28	0.009	0.052	0.214	0.612	1.117	1.593	2.047	2.496
29	0.009	0.052	0.214	0.612	1.117	1.593	2.047	2.496
30	0.009	0.052	0.214	0.612	1.117	1.593	2.047	2.496
31	0.009	0.052	0.214	0.612	1.117	1.593	2.047	2.496
32	0.009	0.052	0.214	0.612	1.117	1.593	2.047	2.496
33	0.009	0.052	0.214	0.612	1.117	1.593	2.047	2.496
34	0.009	0.052	0.214	0.612	1.117	1.593	2.047	2.496
35	0.009	0.052	0.214	0.612	1.117	1.593	2.047	2.496
36	0.009	0.052	0.214	0.612	1.117	1.593	2.047	2.496
37	0.009	0.052	0.214	0.612	1.117	1.593	2.047	2.496
38	0.009	0.052	0.214	0.612	1.117	1.593	2.047	2.496
39	0.009	0.052	0.214	0.612	1.117	1.593	2.047	2.496
40	0.009	0.052	0.214	0.612	1.117	1.593	2.047	2.496

Table 71. Benefits of time savings for vacation trips in dollars per vehicle

Time Saving	Income of Motorist (Thousands of dollars per year)							
(Minutes)	<4	4-6	6-8	8-10	10-12	12-15	15-20	>20
1	0.044	0.050	0.057	0.064	0.073	0.082	0.091	0.102
2	0.087	0.100	0.113	0.129	0.145	0.163	0.183	0.203
3	0.131	0.149	0.170	0.193	0.218	0.245	0.274	0.305
4	0.174	0.199	0.227	0.257	0.291	0.327	0.365	0.407
5	0.218	0.249	0.284	0.322	0.363	0.408	0.457	0.509
6	0.224	0.262	0.306	0.355	0.408	0.467	0.530	0.598
7	0.230	0.276	0.330	0.390	0.457	0.530	0.609	0.694
8	0.236	0.291	0.355	0.427	0.509	0.598	0.694	0.796
9	0.242	0.306	0.381	0.467	0.563	0.669	0.783	0.903
10	0.249	0.322	0.408	0.509	0.621	0.744	0.875	0.013
11	0.256	0.338	0.437	0.552	0.681	0.822	0.971	1.126
12	0.262	0.355	0.467	0.598	0.744	0.903	1.069	1.241
13	0.269	0.372	0.498	0.645	0.809	0.985	1.169	1.357
14	0.276	0.390	0.530	0.694	0.875	1.069	0.270	1.474
15	0.283	0.408	0.562	0.741	0.940	1.150	1.369	1.589
16	0.291	0.425	0.592	0.787	1.003	1.231	1.466	1.704
17	0.298	0.442	0.623	0.834	1.067	1.313	1.566	1.819
18	0.305	0.460	0.655	0.882	1.133	1.396	1.666	1.936
19	0.312	0.479	0.688	0.932	1.200	1.481	1.767	2.052
20	0.320	0.497	0.721	0.982	1.268	1.566	1.868	2.170
21	0.327	0.517	0.755	1.033	1.336	1.652	1.970	2.287
22	0.335	0.536	0.790	1.085	1.406	1.738	2.073	2.404
23	0.343	0.556	0.826	1.139	1.477	1.825	2.175	2.522
24	0.351	0.576	0.862	1.192	1.548	1.903	2.278	2.639
25	0.358	0.597	0.899	1.247	1.619	2.000	2.380	2.756
26	0.367	0.618	0.937	1.302	1.691	2.088	2.483	2.873
27	0.375	0.639	0.975	1.357	1.763	2.176	2.586	2.990
28	0.383	0.661	1.013	1.413	1.836	2.264	2.688	3.107
29	0.391	0.683	1.052	1.470	1.909	2.352	2.791	3.223
30	0.400	0.706	1.092	1.527	1.982	2.440	2.893	3.340
31	0.400	0.706	1.092	1.527	1.982	2.440	2.893	3.340
32	0.400	0.706	1.092	1.527	1.982	2.440	2.893	3.340
33	0.400	0.706	1.092	1.527	1.982	2.440	2.893	3.340
34	0.400	0.706	1.092	1.527	1.982	2.440	2.893	3.340
35	0.400	0.706	1.092	1.527	1.982	2.440	2.893	3.340
36	0.400	0.706	1.092	1.527	1.982	2.440	2.893	3.340
37	0.400	0.706	1.092	1.527	1.982	2.440	2.893	3.340
38	0.400	0.706	1.092	1.527	1.982	2.440	2.893	3.340
39	0.400	0.706	1.092	1.527	1.982	2.440	2.893	3.340
40	0.400	0.706	1.092	1.527	1.982	2.440	2.893	3.340

Table 72. Benefits of time savings for work trips in dollars per person

Time Saving (Minutes)	Income of Motorist (Thousands of dollars per year) <4	4-6	6-8	8-10	10-12	1-15	15-20	>20
1	0.001	0.002	0.003	0.004	0.006	0.008	0.011	0.015
2	0.003	0.004	0.005	0.008	0.011	0.016	0.022	0.031
3	0.004	0.006	0.008	0.012	0.017	0.024	0.034	0.046
4	0.005	0.007	0.011	0.016	0.022	0.032	0.045	0.062
5	0.006	0.009	0.013	0.020	0.028	0.040	0.056	0.077
6	0.009	0.014	0.022	0.034	0.051	0.076	0.108	0.149
7	0.013	0.022	0.036	0.058	0.089	0.132	0.186	0.249
8	0.018	0.033	0.057	0.093	0.145	0.210	0.285	0.365
9	0.026	0.049	0.086	0.143	0.216	0.302	0.393	0.487
10	0.036	0.071	0.127	0.205	0.299	0.401	0.505	0.610
11	0.050	0.100	0.177	0.276	0.387	0.502	0.618	0.732
12	0.068	0.137	0.236	0.354	0.478	0.604	0.729	0.854
13	0.091	0.180	0.300	0.434	0.570	0.706	0.841	0.975
14	0.119	0.230	0.368	0.514	0.661	0.807	0.952	1.096
15	0.137	0.263	0.413	0.570	0.728	0.883	1.037	0.191
16	0.142	0.274	0.434	0.602	0.769	0.934	1.098	1.261
17	0.146	0.286	0.456	0.633	0.811	0.986	1.159	1.331
18	0.151	0.298	0.477	0.666	0.853	1.038	0.220	1.401
19	0.155	0.311	0.500	0.698	0.896	1.090	1.281	1.470
20	0.160	0.323	0.522	0,731	0.939	1.132	1.342	1.540
21	0.165	0.336	0.545	0.765	0.982	1.195	1.403	1.609
22	0.169	0.349	0.569	0.798	1.026	1.247	1.464	1.678
23	0.174	0.363	0.592	0.832	1.069	1.299	1.525	1.748
24	0.179	0.376	0.616	0.866	1.112	1.352	1.586	1.817
25	0.184	0.390	0.640	0.901	1.156	1.404	1.646	1.886
26	0.189	0.404	0.665	0.935	1.199	1.456	1.707	1.955
27	0.195	0.418	0.689	0.969	1.243	1.508	1.767	2.024
28	0.200	0.432	0.714	1.004	1.286	1.560	1.828	2.092
29	0.205	0.447	0.739	1.039	1.330	1.612	1.888	2.161
30	0.210	0.462	0.764	1.073	1.373	1.664	1.958	2.230
31	0.216	0.477	0.789	1.108	1.417	1.715	2.008	2.299
32	0.221	0.492	0.815	1.143	1.460	1.767	2.069	2.367
33	0.227	0.507	0.840	1.177	1.503	1.819	2.129	2.436
34	0.232	0.522	0.866	1.212	1.546	1.871	2.189	2.505
35	o.238	0.538	0.891	1.247	1.590	1.922	2.249	2.573
36	0.244	0.553	0.917	1.281	1.633	1.974	2.309	2.642
37	0.249	0.569	0.943	1.316	1.676	2.025	2.369	2.710
38	0.255	0.585	0.968	1.351	1.719	2.077	2.429	2.779
39	0.261	0.601	0.994	1.385	1.762	2.128	2.489	2.848
40	0.267	0.617	1.020	1.420	1.805	2.180	2.549	2.916

APPENDIX D

Glossary

Activity	- A specific work function which is performed on the pavement, i.e., pavement patching, resurfacing, joint sealing, etc.
Activity Workload	- The quantifiable units of work generated for a work activity, e.g., square yards of patching, linear feet of crack sealing, lane miles of resurfacing, etc.
Available Occupancy Hours	- The hours of a day when work crews are permitted to occupy a roadway.
Closure Category	- A variety of lane closure sequences can be used in the delineation of work zone for activity work crews. Each closure sequence is defined as a closure category. As an example, on an eight-lane freeway, the following six sequences of closure categories are feasible. 1. Close one lane at a time 2. Close two lanes at a time 3. Close three, then one lane 4. Close all lanes and use shoulder 5. Close all lanes and use detour 6. Close all lanes and cross traffic over to opposite lanes
Directional Lanes	- The number of lanes going in a single direction for a given freeway, i.e., on an eight-lane freeway, there are four lanes in one direction.
Influence Zone	- The distance over which vehicles are operated at an average reduced speed due to lane closures on the freeway.
Lane Closure	- The number of directional lanes closed for a work activity, i.e., lane closure 1 is one lane closed, lane closure 2 is two lanes closed, etc.
Maintenance Level	- The number of periods in a year when the workload generated by a roadway will be taken care of. If 100 square yards of patching were the

Maintenance Level (Cont.) - annual workload, then a maintenance level of one would mean that the road was occupied for one period to perform the annual work, i.e., work crews would be sent to the road every day until the total workload generated by the roadway had been taken care of by the work crews. A maintenance level of Two would mean that at two periods in the year, the roadway would be occupied to perform work. Further, only one-half of the annual workload would be available during each period. Finally, if the maintenance level were .2, then the road would only be occupied every fifth year. The workload generated each year would be continually accumulated until it could be taken care of in the fifth year.

Occupancy Interval - Any continuous interval of time when the roadway can be occupied which is less than or equal to 24 hours. As an example, one occupancy interval could be a roadway occupancy which started at 8 A.M. and was terminated at 3 P.M. If crews reoccupied the road at 8 P.M. and stayed until 11 P.M. that would be a second occupancy interval.

Occupancy Period - A period of time when work crews occupy a roadway on a continual basis, i.e., at every occupancy interval opportunity. Where the maintenance level is greater than one, for example 3, the annual workload is divided into three parts. It requires an occupancy period to complete the workload for each of the three parts.

Pavement Analysis Age - The models predicting maintenance workload are a function of pavement age. A pavement deteriorates due to loadings and fails at a rate related to its design life. The workload models are based on a deterioration of the pavement over twenty years. The pavement analysis age is created for use in the workload models to accommodate axle loads and a design life which do not correspond to the twenty-year life associated with the models.

Pollution Day	- The total emissions of CO and HC generated by vehicles operating normally on a freeway of a given length during a 24-hour period. The increase in emissions created during a roadway occupancy are converted into pollution days which therefore represent the days of normal operation required to generate the increased emissions caused by the roadway occupancy.
Simulation Workload	- The total units of work performed during the simulation process in subroutine MAINT. The simulation workload is controlled by the worksite workload and the number of iterations specified for the simulation.
Worksite	- The spot location on the roadway where work crews perform productive work.
Work Zone	- The area on a roadway where work crews can actually perform work. The length of this zone does not include the cone taper used to channel traffic.

APPENDIX E

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☆ U.S. GOVERNMENT PRINTING OFFICE: 1976-211-173/620

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