Lab

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT 13

# RUNNING COST OF MOTOR VEHICLES AS AFFECTED BY HIGHWAY DESIGN

## INTERIM REPORT

HIGHWAY RESEARCH BOARD NATIONAL ACADEMY OF SCIENCES - NATIONAL RESEARCH COUNCIL

## HIGHWAY RESEARCH BOARD 1965

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
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# RUNNING COST OF MOTOR VEHICLES AS AFFECTED BY HIGHWAY DESIGN

## INTERIM REPORT

BY PAUL J. CLAFFEY, THE CATHOLIC UNIVERSITY OF AMERICA
WASHINGTON, D. C.

HIGHWAY RESEARCH BOARD OF THE DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH
NATIONAL ACADEMY OF SCIENCES - NATIONAL RESEARCH COUNCIL 1965

## NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by Highway Planning and Research funds from participating member states of the Association and it receives the full cooperation and support of the Bureau of Public Roads, United States Department of Commerce.

The Highway Research Board of the National Academy of Sciences-National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway departments and by committees of AASHO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Highway Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

This report is one of a series of reports issued from a continuing research program conducted under a three-way agreement entered into in June 1962 by and among the National Academy of Sciences-National Research Council, the American Association of State Highway Officials, and the U. S. Bureau of Public Roads. Individual fiscal agreements are executed annually by the Academy-Research Council, the Bureau of Public Roads, and participating state highway departments, members of the American Association of State Highway

This report was prepared by the contracting research agency. It has been reviewed by the appropriate Advisory Panel for clarity, documentation, and fulfillment of the contract. It has been accepted by the Highway Research Board and published in the interest of an effectual dissemination of findings and their application in the formulation of policies, procedures, and practices in the subject problem area.

The opinions and conclusions expressed or implied in these reports are those of the research agencies that performed the research. They are not necessarily those of the Highway Research Board, the National Academy of Sciences, the Bureau of Public Roads, the American Association of State Highway Officials, nor of the individual states participating in the Program.

NCHRP Project 2-5 FY '63
NAS-NRC Publication 1212
Library of Congress Catalog Card Number: 65-60038

# FOREWORD

*By Staff*

*Highway Research Board*

The highway planner, economist, traffic and design engineer will find in this interim report information on automobile fuel consumption which may be readily applied to existing and proposed roadway studies. The use of a precise fuelmeter developed for this study, and the strict survey control provided during data collection operations, make the results presented in this report the most accurate known to date. In addition to the fuel consumption study, an annotated bibliography is included on the subject of motor vehicle operating costs, and brief discussions are furnished of research conducted on such factors as tire wear, oil consumption, maintenance, and depreciation, which contribute to the overall operating cost of the motor vehicle.

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This research effort was initiated to update and to produce more accurate vehicle running cost information for use in highway economic studies. Vehicle running costs are a part of user's costs that can be directly related to highway geometrics and traffic operating characteristics for use in detailed running cost analyses of new highway projects, and in comparisons of running costs on alternate routes or under various operating conditions.

A precise electronic fuelmeter developed by the research agency records fuel consumption to the nearest 5 cc. Thus device, utilizing photo-electronic principles, is considered to be a major contribution to the development of fuel meters.

Actual field measurements of fuel consumption of a standard passenger vehicle were made by the research agency. More than 4,000 test runs were conducted in which fuel consumption rates of the survey vehicle were measured at various speeds ranging from 10 to 80 mph. The fuel consumption and vehicular speeds were further related to pavement types and to roadway grades ranging from plus 8 percent to minus 8 percent. A study was also made of the fuel and time consumption of the survey vehicle during normal deceleration and acceleration for the various speed ranges. The results of these tests are presented in tabular form so that they may be easily applied to the economic analysis of roadway improvements. Methods of measuring tire wear are evaluated and results of a field test conducted with the survey vehicle on a 65-ft radius curve driven at 20 mph are discussed.

This research project is being continued for a second year to provide more detailed running cost information for a greater variety of vehicle types. The fuelmeter will be installed in rented cars and trucks to extend the fuel consumption results of the first year's work. Test runs also will be conducted to relate fuel consumption with the horizontal curvature of the roadway and tire wear tests will be made to determine costs as related to vehicle speed, pavement type, and roadway curvature. Studies will continue on oil consumption, maintenance, and depreciation in an attempt to relate these factors to roadway system characteristics.

This project has provided a significant contribution to the development of relationships among vehicle operating costs, highway location, geometric design, and traffic controls. The precise measurements and strict survey controls have made possible more accurate data than those from any previous study known.

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## ACKNOWLEDGMENTS

The research reported herein required the services and cooperation of several individuals and agencies. Special acknowledgment is given to the following:

Joseph C. Michalowicz, Associate Professor of Electrical Engineering and Head, Electrical Engineering Department, The Catholic University of America (Washington, D. C.), for development and operation of the special photo-electronic fuelmeter used in the fuel consumption tests; Dale C. Braungart, Associate Professor of Biology, and Frank A. Biberstein, Professor of Civil Engineering, The Catholic University, for refinement and operation of the radioisotope method used in the tire wear studies; Hoy Stevens, Consulting Mechanical-Automotive Engineer, Washington, D. C., who made the engine oil consumption rate study; the Maryland State Roads Commission and Henry Eastburn Co., Contractors, for permission to use the I495 (Capital Beltway) test site locations; the U. S. Air Force, Department of Defense, for use of the Bolling Air Force Base test site locations; D. C. Transit Company, Washington, D. C., for use of its dynamometer testing facility and personnel; and Philip L. Brach, Assistant Professor of Civil Engineering, The Catholic University of America, for preparation of the annotated bibliography of motor vehicle operating costs.

The author, as Professor of Civil Engineering, The Catholic University of America, was the project director for the work reported herein.

# RUNNING COST OF MOTOR VEHICLES AS AFFECTED BY HIGHWAY DESIGN

## INTERIM REPORT

## SUMMARY

The primary results of this first phase of research into the effects of highway and traffic conditions on motor vehicle running costs are (a) determination of detailed information on passenger car fuel consumption rates for a variety of road and traffic conditions, (b) development of a dependable precision electronic fuelmeter, and (c) compilation of a complete bibliography of motor vehicle operating cost. Related but less extensive investigations were also made to devise an improved method for measuring tire wear and to develop suitable approaches for estimating engine lubrication costs, maintenance costs, and depreciation costs.

The passenger car fuel consumption rates were determined by carefully measuring the fuel consumption rates of a typical vehicle as these are affected by vehicle speed, road surface condition, gradients, curvature, and vehicle speed changes. To assure the validity of the results several special studies were included to determine the effect on the accuracy of fuel consumption measurements of each of the following: wind velocity, vehicle weight, fuel characteristics, vehicle operating efficiency, and differences in driver techniques of throttle manipulation.

It was necessary to develop the precision electronic fuelmeter before proceeding with the measurement of fuel consumption rates for the passenger car because no dependably accurate meter capable of highly precise measurement existed at the time the study was conducted. A full description of this meter, its manner of operation and the service characteristics obtainable, are presented in an appendix. Another appendix comprising an annotated bibliography of current publications dealing with motor vehicle operating costs and their measurement includes all pertinent books, pamphlets, reports, bulletins and periodical articles published between 1948 and 1962.

The vehicle used for the passenger car fuel consumption study was a new 8-cylinder 1964 sedan of American make with automatic transmission and weighing 4,175 lb when loaded for the test runs. The fuelmeter was of the buret type, with an electronic device for automatically opening and closing valves and for automatically recording the fuel used to the nearest 5 cc.

Test runs were made at each of several sites at which appropriate study conditions were available. The primary test site, however, was a section of Interstate 495 (Capital Beltway) near Andrews Air Force Base, Washington, D. C. This road was available for making test runs without interference by traffic during a five-week period after it had been completed but before it was opened to traffic.

The results of the fuel consumption measurements are presented in a series of graphs and tables, together with the result of special fuel measurements designed to assure the accuracy of the fuel consumption study.

Of special interest are the compilations of how the fuel consumption rates of

passenger cars (in gallons per mile, miles per gallon, and gallons per hour) vary with vehicle speed for a full range of speeds from 0 to 80 mph. The road conditions for which these data were obtained were those for minimum resistance to movement —level and straight with a high-type surface and no wind. All values are for uniform speeds of travel maintained at a steady manifold vacuum.

Fuel consumption costs are given for corresponding fuel consumption rates for the operation of a passenger car on uniform grades where in all other respects road conditions are those for minimum resistance to movement.

Information is also given on the fuel consumption costs of passenger cars on level straight roads where rough or unpaved surface conditions exist, as well as on the excess fuel and time costs that arise as a result of vehicle stops and slowdowns from initial speeds of from 5 to 60 mph.

The optimum speed for passenger car fuel economy on level straight high-type pavement is a steady 35 mph. At this speed, the fuel consumption rate is 20.7 miles per gallon for a 4,000-lb gross weight vehicle. The same vehicle achieves only 13.4 miles per gallon at a steady 80 mph and only 10.9 miles per gallon at a steady 8 mph.

The fuel consumption rate of the passenger car, loaded at 4,000 lb, is only reduced by 0.9 (20.7 to 19.8) miles per gallon when operated at a steady 35 mph on bituminous-treated gravel surface rather than paved surface. It is reduced by 12.0 (20.7 to 8.7) miles per gallon for operation on a +8 percent grade rather than on the level.

Passenger car fuel consumption, noted previously as 20.7 miles per gallon at 35 mph, is reduced to 17.5 miles per gallon if the vehicle is brought to a momentary stop once in each mile. On a level high-type pavement at 20 mph the fuel consumption is reduced from 19.1 miles per gallon for operation on a straight alignment to 9.6 miles per gallon for operation on a 65-ft radius curve and to 17.9 miles per gallon for operation on a 955-ft radius curve.

CHAPTER ONE

# INTRODUCTION

The motor vehicle operating costs investigated for this study included all costs directly related to the ordinary operation of highway vehicles that are subject to change as a result of changes either in highway design or in conditions of traffic flow. Highway transportation costs that are essentially oriented to the user (delay and discomfort costs, for example) and those of an extraordinary nature (accident costs) are excluded except as they impinge obliquely on other vehicle costs. Specifically, five categories of operating cost were examined—fuel cost, tire wear cost, oil cost, maintenance cost, and depreciation.

The highway design elements which may have direct effects on vehicle operating costs, especially fuel cost, are gradients, curvature, surface roughness, and route length. Traffic conditions that affect operating costs for a road of given design are those that impose speed reductions on vehicles (stops and slowdowns), including traffic conflicts at highway crossings, conflicts at merging points, and inter-vehicle conflicts when traffic volumes exceed the capacity of a given road design.

The study objectives were twofold—to develop appropriate procedures and equipment for investigating the effect of highway and traffic conditions on motor vehicle operating costs (where existing equipment and procedures are unsatisfactory), and to measure the cost of fuel consumed by a passenger car for a variety of highway and traffic conditions. The first objective provides for establishing the best methods of accumulating useful information for each of the five categories of operating cost; the second encompasses development of an extensive array of data for one of these categories, vehicle fuel consumption, for one type of highway vehicle, the passenger car.

The approach selected for achieving the project objectives involved making five closely related studies. One, a review of relevant information either existing or in the process of development at the time the project was begun, was carried out first to provide bibliographical material and other information to help guard against inadvertently repeating the efforts of others. The principal part of the investigation, the measurement and analysis of fuel consumption data for a passenger car as affected by each of several highway and traffic conditions, was conducted last. Three other separate studies were made after completion of the literature review and before the passenger car fuel consumption study was made, including: (a) development of a precision electronic fuelmeter; (b) investigation of a radioisotope technique for measuring tire wear; and (c) review of methods for estimating engine lubrication costs, maintenance costs, and depreciation costs.

The findings of the principal part of the investigation, measurement of the fuel consumption of a passenger car as affected by highway and traffic conditions, together with a discussion of the research approach used and an appraisal of these findings, constitute the body of this report. The major results of two of the supporting studies —the review of the literature and current research projects concerning motor vehicle operating costs and the development of a precision electronic fuelmeter—are presented in Appendices A and B, respectively. The results of the investigations of radioisotope techniques for tire wear measurement and of methods for estimating engine lubrication costs, maintenance costs, and depreciation costs are discussed in succeeding paragraphs of this introduction.

## REVIEW OF LITERATURE AND CURRENT RESEARCH PROJECTS

Two studies were undertaken to determine what relevant information on motor vehicle operating costs were in existence or being developed by others. The first of these, a thorough literature search, encompassed all books, pamphlets, periodical articles, and study reports concerning motor vehicle operating costs published during the period from 1948 to 1962, inclusive. Each publication found to offer useful and pertinent information concerning motor vehicle operating costs as affected by highway and traffic conditions has been included in the annotated bibliography of motor vehicle operating costs (Appendix A).

The second, a canvass of persons interested in research into motor vehicle operating costs to establish the current status of this type of research, was accomplished with a mail questionnaire designed to obtain both a clear understanding of the scope and objectives of research in progress and an inventory of special equipment available for motor vehicle cost studies. Special care was taken in preparing the questionnaire to insure that the necessary information could be obtained without imposing a burden on respondents.

Fifty-two copies of the questionnaire were distributed to persons interested in highway engineering research all over the world. Of these, 28 were completed and returned, a 54 percent response. In effect, however, the response was much better than this, inasmuch as all engineers and administrators most likely to be involved in motor vehicle operating cost research, or to know of research in progress, were included among those who responded to the inquiry. In respect to this latter group, the response was almost 100 percent.

The information contained in the returned questionnaire demonstrated that most current research projects relating motor vehicle operating costs to highway design are being undertaken by organizations who regard their research findings as private information (automobile and tire manufacturers, oil producers, and others). Studies in progress which may result in published reports are of a limited nature, often concerned only with particular local conditions.

Because the replies to the questionnaire indicated that no comprehensive studies of motor vehicle operating costs are in progress by organizations free to publish their research results, no attempt has been made to include a tabulation of the results of the inquiry in this report. Information on the few limited studies in progress and on the availability of special study equipment, as determined from the survey, is referred to herein only as appropriate in connection with discussions of research plans for determining motor vehicle operating costs.

## DEVELOPMENT OF A SUITABLE FUELMETER

The most important requirement for a successful study of motor vehicle fuel costs, as these are affected by highway and traffic conditions, is a dependable fuelmeter of high precision and accuracy. Fuel consumption must be examined with great precision because it is sensitive to small changes in highway conditions. Fuel consumption investigations are difficult to make, however, inasmuch as study sites where the effect of each of several conditions on fuel consumption can be examined are limited to sections of highways so short that the fuel consumption necessary to travel the full length often is less than 200 cc. Measurement of the fuel consumption for operation over these short test sites such that the difference due to difference in the design characteristics of each can be determined, is impossible unless a dependable meter is able to measure accurately very small units of fuel consumption.

Because none of the fuelmeters available for this project was designed to give dependably accurate fuel measurements of high precision under the severe conditions imposed by the nature of the study (continuous operation for long periods of time, rapid changes in rates of fuel flow, a wide range of fuel temperature, and variations in fuel pressure, for example), it was necessary, as part of this project, to design and build a fuelmeter having the characteristics needed. In Appendix B the meter's inventor describes its development and operation, together with the type of service it can provide.

## TIRE WEAR

The effect of tire wear on the total cost of motor vehicle operation, as this cost is affected by highway and traffic conditions, is second in magnitude only to that of fuel consumption. Tires are in direct contact with roadway surface and their wear is affected by the highway design

*Figure 1. Pattern of tread wear of a set of tires for a passenger car driven 22 miles at 20 mph counterclockwise on a 65-ft radius circle, including 33 momentary stops. The right front and left rear tires are unusable, although each tire has only traveled 4,200 miles.*

elements of surface roughness, curvature, and gradient, and by vehicle speed changes, both stops and slowdowns.

Sharp curvature is particularly destructive of tire tread. Figure 1 shows the tire tread wear that results when a passenger car is operated for 3 hr counterclockwise on a curve of 65-ft radius at 20 mph, covering a travel distance of 22 miles with 33 stops. Each tire had excellent tread at the beginning of this operation, having had only 4,200 miles of service, 80 percent of which had been on straight level roadway at uniform travel speeds (uniform speed fuel consumption tests). Both the right front and left rear tires were worn to the point of failure by this test, with the remaining two tires still showing good tread. At least 80 percent of the tire life (and tire cost) of these two tires was expended during 22 miles of travel on this curve. At this rate the full life of the tires would be used up in 27.5 miles of such travel.

Loss of tire tread on sharp curves as used in this test constitutes a problem of growing importance as the frequency of cloverleaf-type interchanges grows with the construction of new expressways and freeways. Left-turning vehicles at cloverleaf intersections must turn through 270° rather than 90° as for a direct left turn. If the radius of the left-turn ramp is 65 ft, the additional curve travel due to the extra 180° of arc is 0.038 miles. The number of times a vehicle can be turned this extra length of arc before two tires (one front and one rear) will be worn out, found by dividing 27.5 miles of tire life on the curve by 0.038 extra miles per turn, is 723 turns. Thus, a commuter who had to negotiate four such left-turn ramps getting to and from work daily would wear out two tires yearly solely from this cause (unless he rotates tires regularly).

The effect of most highway and traffic factors on tire wear is much less evident, however, than that for an extremely sharp curve such as the 65-ft radius curve. For example, excess tire tread lost through operation on a 1° curve as compared to operation on a straight alignment, or for travel on a bituminous-treated gravel surface rather than on a high-type pavement, is very small, perhaps on the order of 0.00001 in. per mile. Using existing means for measuring tire wear it would be necessary to have test sections with identical tire wear characteristics throughout for a length of 1,000 miles or more in order to measure accurately the effects on tire wear of differences in these highway factors. Inasmuch as very few such test sections are available, the effect of many highway design characteristics on tire wear would be impossible or at least very expensive to determine with present equipment.

### *Radioisotope Technique for Measuring Tire Wear*

It was thought that industrial methods using radioisotopes to measure the thickness of material might provide a scientific means for convenient measurement of tire wear. Accordingly, experiments were designed to determine a relationship between tire wear and the absorption of radioactivity by the tire in an effort to provide a new means for measuring reduction in tread thickness and tire weight which might gain an advantage over existing methods of tire wear measurement in precision while eliminating the inconvenience of returning the tire to the laboratory and the necessity of a systematic preparation of the tire before measuring or weighing. These resulted in a proposed method for using radioisotopes for tire wear studies, and the experiments to test it.

However, the results of this research are not of immediate use for road user cost studies, largely because of the variability of radioactive absorption noted in tire rubber. To use this technique it is necessary to establish a specific correlation between radioactive absorption and tire thickness for each separate tire, inasmuch as no single correlation curve is suitable for more than one tire. Thus the technique at present is useful mainly for multiple studies of a single tire.

Furthermore, although field measurements of tire wear can be made more easily using the radioisotope method than by using a tire gauge, the precision is about the same in each case. The most precise method of tire wear measurement, albeit the most inconvenient, is by tire weight.

### *Tire Wear Measurement for This Study*

Tire wear measurements for determining the effects of various highway and vehicle operating conditions on tire wear will be made by weighing the whole tire before and after each set of test runs using highly precise scales. Although this is an inconvenient process, it is the most precise technique of dependable accuracy that is available for determining the magnitude of small amounts of tire wear. Specially designed scales patterned after those developed for tire wear measurements by the National Bureau of Standards will be used.

## ESTIMATION OF ENGINE LUBRICATION COST

A comprehensive review of engine lubrication requirements, especially as these are affected by highway conditions, was made to determine the best method of estimating engine lubrication cost. This review included an analysis of the effects of vehicle type, vehicle maintenance, conditions of vehicle use, oil filter use, and oil characteristics, as well as consideration of the effects of road conditions, on oil consumption rates. Particular attention was given to the manner in which engineering advancements in engine design and construction are reducing oil consumption for all types of vehicles. Furthermore, oil consumption rates of all vehicle types are closely related to vehicle maintenance; that is, a well-maintained engine will have low oil consumption even on a road having poor design characteristics, whereas a poorly maintained vehicle will use excessive oil even on the highest type of road.

It is noted that for vehicles taken as a group, the only highway factor that may be related to oil consumption is road length. That is, an average rate of oil consumption may be determined in gallons per mile for operation under conditions typical of modern roads and modern speeds. In road user cost studies this item would be included as a standard cost per mile by vehicle type.

However, for certain vehicle types and for certain engine conditions, particularly for older engines that are not well maintained, the effect on oil consumption of prolonged heavy engine loads as encountered on long steep grades or when accelerating during the execution of a passing maneuver at high speed is probably significant. The effect of heavy loads on the oil consumption rates of such engines could be measured by noting oil consumption for sustained heavy loads applied to stationary engines.

Engine lubrication costs for this study will be determined for each of the main categories of vehicle types for operation on paved roads and for operation on gravel roads; at speeds typical of urban roads and at speeds typical of rural roads. These data will be obtained by interviews with fleet operators, vehicle manufacturers' representatives, oil company representatives, and service station operators, and by examination of pertinent records of vehicle oil consumption from various sources. The accumulation and the analysis of these data will be in accordance with specific procedures established as a result of the previously mentioned study. The details of these procedures are not included in this interim report, but will be included in the final report with the full schedule of data obtained on vehicle oil consumption rates.

## ESTIMATION OF VEHICLE MAINTENANCE COSTS

There are many difficulties in determining how the maintenance or repair costs of motor vehicles are related to highway and traffic conditions. Numerous variable elements are involved, including the average level of preventive maintenance adhered to by each category of vehicle owner, and the characteristics of the service for which vehicles are used. Certain items of maintenance are undoubtedly related to specific highway conditions, such as the relationship between brake and transmission maintenance costs and the frequency of vehicle stops, the effect of rough road surfaces on the cost of maintaining vehicle suspension systems, and the cost of more frequent engine repairs when vehicle operation is predominantly on steep grades. At present, however, data for relating maintenance costs to these and other highway conditions are unavailable except for the general records on vehicle maintenance costs, by mile of use and by type of service, kept by most operators of commercial fleets.

Data on maintenance costs as affected by certain highway conditions can be obtained if certain records of vehicle use and repair are kept. For example, because the wear on brake and transmission parts is obviously closely related to the frequency of stop-and-go operations, the specific relation could be established by arranging for a selected group of vehicle operators to keep a record of vehicle stops and a corresponding record of brake and transmission repair costs. Likewise, operators using vehicles entirely on roads with a high-type pavement, and those using similar vehicles but operating them exclusively on a rough or low-type surface, could be invited to keep records of both vehicle mileage and vehicle suspension system repair costs. Recording of this kind of data can be simplified by using commercial devices that automatically record much of the needed information. Data such as these have been recorded continuously, without any special difficulty or inconvenience, for operation of the test vehicle used for this study since its purchase in February 1964.

A recommended approach for obtaining useful data on vehicle maintenance costs as affected by highway and traffic conditions using existing data is to review the maintenance records for selected groups of vehicles for which data on past operations can be determined. To do this it will be necessary to identify, for each of the various categories of vehicles, groups of vehicles that are used for a given type of service on a particular route; also, to study the records normally kept for these vehicles on the characteristics of their service, the mileage when repairs are made, and the type and cost of the repairs. For example, passenger cars could be represented by a fleet used to provide limousine service between the airport and the downtown air terminal building of a large city. Transit buses could be represented by those buses assigned permanently to a particular shuttle service. Small trucks (two- and three-axle vehicles) could be typified by wholesale delivery trucks used exclusively to move produce from a particular market to a particular store, and large tractor-trailer combinations could be represented by shipper-owned fleets used for special movements, such as from a mine to a smelter plant. For each of these representative groups, information could be obtained concerning type of road surface and gradients on which the vehicles operated, frequency of stop-and-go operations, normal running speeds, and total accumulated mileage, as well as information on repairs and repair costs.

Data on road and traffic conditions for a study of this type would have to be measured by the researcher, inasmuch as this information is not normally maintained by vehicle owners. Items of survey equipment particularly useful for this purpose are easily available. They include automatic traffic counters, a precise distance measuring wheel designed to be drawn behind a passenger car, and instruments for measuring gradients and curvature.

Data on vehicle repairs and repair costs, daily travel mileage, and trip frequency would have to be obtained from the operators of the vehicles selected for study. The best method of obtaining this information would be by personal interviews with the people responsible for keeping these records.

This approach, if carried out properly, should produce highly useful information on the maintenance costs of motor vehicles as affected by highway and traffic conditions, at least for those repair costs most closely related to highway and traffic factors.

## ESTIMATION OF VEHICLE DEPRECIATION

The problem of determining whether or not highway and/or traffic conditions contribute to the cost of depreciation of a properly maintained motor vehicle, and if so how much, is difficult, surrounded as it is by much uncertainty and controversy. Numerous investigators believe that depreciation cost is almost entirely unaffected by use. Others suggest that about one-half of vehicle depreciation cost is due to miles of travel accumulated by a vehicle, arguing that if a vehicle were not operated at all, its depreciation cost would be about 50 percent of what it is after being used. Still others claim that, at least for passenger cars, depreciation is partially due to vehicle use, not as measured by miles of travel but as measured by such matters as frequency of stop-and-go operations, frequency of persons entering or leaving the vehicle by sliding over the seats, and the type of service performed by the vehicle.

The only way in which the depreciation cost of a vehicle relative to its use can be estimated with reasonable accuracy is to purchase three vehicles (new passenger cars, for example), each identical to the others in every way, and assign one to normal service, place one where it is exposed to weather and arrange for persons to enter and leave as often as would be normal for a passenger car but without the vehicle being moved, and leave the third car entirely alone in an area where it is exposed to weather. At the end of some period (one or two years), the three vehicles should be offered for sale. The differences in average bid prices received for the three cars would be measures of the effects of both travel and non-travel use on the depreciation cost of the vehicles. Maintenance procedures should be such as to keep all three vehicles in excellent operating condition throughout the study period.

To make investigation of the effect of travel on the depreciation of passenger cars most useful, a series of four three-car study groups should be used, each group distinguished from the others by the age of the cars at the beginning of the study period. In addition to the new car group previously discussed, a second group might be made up of identical three-year-old cars, a third of identical six-year-old cars and a fourth of identical ten-year-old cars. Each three-car group should be investigated as described in the previous paragraph.

CHAPTER TWO

# RESEARCH APPROACH TO PASSENGER CAR FUEL CONSUMPTION COST

The key feature of this study of passenger car fuel consumption rates is the use of a highly accurate and dependable means for measuring and recording fuel consumption rates as they are affected by a wide variety of operating conditions and highway design elements. Accuracy of results was assured by careful selection of test sites, use of a fuelmeter specifically designed for these types of measurements, careful control of the fuel supply, frequent inspections of vehicle elements affecting fuel economy, and field data collecting procedures designed for maximum accuracy of results.

The fuel consumption rates reported herein are for passenger car operation only, although the study procedures developed for this project are equally applicable for investigation of fuel consumption for all types of motor vehicles. The test vehicle for which all data were collected was selected as being most nearly representative of new automobiles on American highways in 1964. It is a 4-door 8-cylinder standard American-made sedan with automatic transmission and weighs 3,600 lb empty.

In general, test runs were made with a 4,175-lb total loaded vehicle weight. However, as reported in Chapter Four, certain measurements were made while carrying an additional weight of 500 lb distributed about the vehicle. These runs were designed to develop information on the effect of vehicle weight on passenger car fuel consumption for a limited range of weights.

Most fuel consumption data collected for this report were obtained under calm wind (3 mph or less) conditions. However, because actual passenger car operations are as likely to be made when wind velocities exceed those for calm conditions as when calm conditions prevail, certain test runs were made for a series of moderate wind velocities when wind direction was either in the same or in opposing direction as that in which the vehicle was operated. Thus, the data reported in Chapter Three include information on the effects of certain wind conditions on passenger car fuel consumption.

Fuel consumption data were investigated for ten conditions of highway design (road conditions), as follows:

1. Paved straight roadway having nearly zero gradients.
2. Paved straight roadway with gradients typical of the minimum grade conditions found in many areas (an 0.8 percent plus grade, a flat vertical curve, and an 0.8 percent minus grade, in sequence and all of about equal length).
3. Bituminous-treated gravel surface on straight roadway with gradients typical of the minimum grade conditions found in many areas (an 0.8 percent plus grade, a flat vertical curve, and an 0.8 percent minus grade, in sequence and all of about equal length).
4. A smooth, sandy-gravel surface on straight level alignment.
5. Paved straight grades having uniform gradients in one direction of 0.8 percent, 2.1 percent, and 8.0 percent.
6. Gravel-surfaced straight alignment having a gradient of 1.0 percent for a quarter of its length with the remainder at 2.0 percent.
7. Paved level roadway on a curve having a 65-ft radius.
8. Paved level roadway on a curve having a 955-ft radius.
9. Intersections where vehicles must stop for a traffic light or for a stop sign (stop-and-go operations).
10. Intersections, crossroads, access points and curves where vehicles are required by law or forced by conditions to slow down momentarily (slowdown operations).

For each of the first eight of these highway design or road conditions, precise fuel consumption rates in gallons per mile were determined for operation at each of several uniform speeds. In the case of paved and nearly level surfaces (condition 2), fuel consumption rates were investigated for 10, 20, 25, 30, 40, 50, 60, 70, and 80 mph. For conditions 1, 3, 4, 5, 6, 7, and 8 fuel consumption rates were measured for a smaller range of speeds, in most instances with speeds limited by the particular study conditions. For example, operating speeds on a curve having a 65-ft radius (condition 7) could not be made safely at speeds in excess of 20 mph.

Information on both the fuel and time consumed in excess of that for uniform speeds was found both for stop-and-go operations (condition 9) and for slowdown operations (condition 10). In each case the test vehicle's speed was reduced from a given running speed (initial speed) either to a stop or to a particular lower speed and the running speed was then immediately resumed. Running speeds of 10, 20, 30, 40, 50, and 60 mph were employed for these studies. The field tests were made on paved straight roads having gradients typical of the minimum grade conditions found in many areas, as previously described for condition 2. Acceleration and deceleration rates were 5 ft/sec/sec, except that acceleration above 30 mph was at a rate of 2.5 ft/sec/sec.

## SELECTION OF TEST SITE

Successful completion of this study was due in no small part to the thorough survey conducted to locate appropriate test sites. Many sites within 100 miles of Washington, D. C., were examined. The search was complicated by the necessity that the sites chosen for particular runs not only be appropriate for the test involved but also provide convenient means for the turning of vehicles and be free of heavy traffic volumes that would interfere with test operations.

The primary test site selected for this study consisted of a section of the westbound lanes of Interstate 495 (Capital Beltway) near Andrews Air Force Base, Md. This road was nearly straight and had a newly constructed, high-type concrete surface. In profile it consisted of an 0.8 percent uniform positive grade 1,150 ft in length, followed by an 800-ft vertical curve (crest), then an 0.8 percent uniform negative grade. All test runs on this section were made after the road was constructed but before it was opened to traffic. Thus, the test vehicle could be turned easily and no traffic flow interfered with test operations. All test runs for conditions 2, 9, and 10, as well as runs on an 0.8 percent grade for condition 5, were made at this site.

The roadway used for operations on bituminous-treated gravel surface (condition 3), was the partially completed shoulder of the primary test site. At the time of the tests this shoulder consisted of a compacted soil-cement base overlaid with a surface of ½- to 1½-in. diameter gravel particles bound together with a surface application of bituminous material. It was firm and stable, but quite rough, generally representative of a low-type penetration macadam surface. In length, alignment and profile this section was identical to the primary test site.

Although the grades existing at the primary test site were very flat (0.8 percent) and balanced by direction, it was deemed wise for purposes of this study to conduct as many uniform speed runs as possible on paved routes having nearly 100 percent level profiles (condition 1). Therefore, uniform speed runs were made at 10, 20, and 30 mph on nearly level Taxiway 10 at Bolling Air Force Base, Washington, D. C., and at 30, 40, and 50 mph on a level section of the Suitland Parkway near Washington, D. C. It is worth noting that it was very difficult to find these nearly level sections of rural highway, inasmuch as the typical so-called level road almost always has a gradient of at least 0.5 percent and often as much as 1.0 percent. Typical minimum grade conditions on United States highways, in the East and Northeast at least, are much better represented by the grades of the primary test site than by those of the nearly level test sites.

Taxiway 10 at Bolling Air Force Base was also the site chosen for studies of fuel consumption on curves, specifically for conditions 7 and 8. This facility is paved, level, and clear, with a width of 150 ft and a length of more than 3,500 ft.

To make the fuel consumption measurements for operation under condition 7, a circle was marked out on the surface of the runway and the test vehicle was operated so that its center followed a circle of 65-ft radius.

Test operations to determine fuel consumption rates on a curve having a 955-ft radius (6° curve) were also made on Taxiway 10, although in this case there was insufficient space to use a full circle. However, it was possible to lay out a 1,000-ft arc of a curve having this radius in such a way that the test vehicle could approach and leave the curve on a tangent paved surface. To identify the fuel consumption due to the curvature alone, test runs were also made on a straight test path 1,000 ft in length laid out parallel to the long chord of the curve and at the midpoint of its middle ordinate.

The sites picked for determination of fuel consumption on various grades having straight alignment and a high-type pavement (condition 5) were located on US 40 15 miles west of Frederick, Md. (8.0 percent grade), and on US 240 10 miles south of Frederick, Md. (2.1 percent grade). In addition, fuel consumption data for operation on an 0.8 percent grade were obtained at the primary test site, as previously mentioned in connection with conditions 2, 3, 9 and 10. Each grade on which test runs were made had an almost perfectly uniform grade at least 2,500 ft long. Traffic volumes on these roads were low enough during the middle of the day to permit test runs to be made without traffic interference.

Data on fuel consumption rates also were obtained for operation on a straight nearly level road having a smooth surface of sand and fine gravel (condition 4) and on a straight road with a loose gravel surface varying in profile from 1 to 2 percent (condition 6). These study sites, each more than 2,000 ft long, are portions of the unpaved roadway now occupying the space reserved for future construction of westbound lanes for the Suitland Parkway near Morningside, Md.

### FUELMETER

Fuel consumption measurements for all test runs were made using the photo-electronic fuelmeter developed at Catholic University specifically for this purpose. This meter counts each 5-cc unit of fuel used by a vehicle's engine without being affected by fuel temperature, fuel pressure, rate of fuel flow, or vehicle motion. The total count of these units of fuel consumption for each test run appears as the reading of a dial indicator which is reset to zero after each run. The photo-electronic fuelmeter is fully described in Appendix B.

### FUEL

The same brand of regular grade gasoline was used as fuel for all test runs to eliminate variations in the study results arising from the differences which might exist among different brands or types of gasoline. As an additional guard against introducing errors in the study data through variations in fuel characteristics, all fuel was taken from the same supply tank, which was replenished only twice during the course of the study. As a further refinement, a specimen of the fuel originally in the supply tank, plus specimens of the fuel used to replenish the supply tank each time this was done, were examined for variations in specific gravity, a good indicator of variations in heat content. These three specimens, designated as fuels 1, 2, and 3 and representing all of the fuel used in the study, were found to be essentially the same. Thus, the consistency of the fuel characteristics important to the accuracy of the research was assured.

### INSPECTION OF VEHICLE ELEMENTS AFFECTING FUEL ECONOMY

Extreme care was exercised during the test period to detect any internal changes in the test vehicle's engine or in any part of its running gear that might affect fuel economy and cause variations in study results. Inspection programs instituted at the beginning of the test and adhered to throughout the test period included (a) periodic examination of engine efficiency and power output, (b) weekly examination of front wheel toe-in, and (c) daily notation of tire radii and pressures and engine idling vacuum readings.

The engine efficiency and power output characteristics of the test vehicle were examined by placing the vehicle on a chassis dynamometer, attaching an exhaust gas analyzer, and noting the air-fuel ratio and horsepower at various speeds and at various dynamometer-imposed loads. Three such examinations—at the beginning, at the midpoint, and at the end of the five-week field testing period—showed that the engine efficiency and power output of the test vehicle remained nearly constant for the full period of data collection.

Toe-in of the front wheels (angular relationship between the steering wheels) of the test vehicle was measured each week to detect discrepancies which would cause variation in vehicle rolling resistance. No such discrepancies were noted, however, giving assurance that the front wheels were properly aligned throughout the test period.

Tire radii, tire pressures, and engine idling vacuum readings were taken three times each day—at the beginning of the work day, at noon, and at the end of the work day. Tire radii and pressure readings were taken to make certain that these factors, which affect rolling resistance, remained unchanged during the test period. When deviations were noted, corrections were made by increasing or decreasing tire pressure. The idling engine vacuum readings were a convenient means of providing daily verification of consistency in engine operating characteristics.

## FIELD DATA COLLECTING PROCEDURE

A major factor contributing to the accuracy of the fuel consumption data was a field data collection procedure carefully designed to eliminate the variable effects on fuel consumption of different wind conditions, methods of throttle operation relative to road conditions, and fuel temperatures. This procedure consisted of a basic study technique with special provisions for excluding the effects of these three conditions.

The basic study technique adhered to for all test runs provided for operation of the test vehicle at a particular run speed between two flags identifying the end points of the test section. The fuel and time consumed in traversing the distance between the flags were measured with the photo-electronic fuelmeter and an accurate stopwatch. Because the fuelmeter counted fuel consumption in fixed units of 5 cc, fuel consumption was recorded as the difference between the two meter readings immediately after the vehicle passed the beginning and end points of the test section. A second stopwatch was used to record to the nearest 0.1 sec the time between when the fuelmeter dial first changed after the beginning point was passed and when it first changed after the final point was passed. A carefully calibrated survey speedometer mounted directly in front of the driver's seat enabled the driver to maintain run speeds without difficulty.

The effects of wind conditions on the fuel consumption of the test vehicle were examined early in the study period by operating the vehicle for a series of runs for condition 2 at various speeds with winds of different velocities acting generally parallel to the direction of the test runs. As might be expected, wind was found to exert a significant influence on the rate of fuel consumption when tests were made with winds of 8 mph or more acting parallel to the movement of the test vehicle. The results of these test runs are presented in Chapter Four.

The effect of wind conditions on fuel consumption was eliminated by conducting test runs only when winds were calm (3 mph or less) or when winds of 4 and 5 mph blew steadily along a line closely parallel to the direction of vehicle travel. In the latter situation the effect of the wind was canceled by averaging fuel consumption rates in both directions. All test runs were made between June 1 and July 6, when a high percentage of days with calm wind conditions would be expected at the test sites. Only test sites aligned in an easterly direction were selected, as this is approximately collinear with the direction of prevailing winds. Winds with velocities above 5 mph were unusual, but when they did occur testing was suspended.

The importance of variations in throttle position on fuel consumption rates was demonstrated during the first few days of the test program. In these early test runs the driver was instructed to maintain run speed by manipulating the throttle as necessary to maintain a constant speedometer reading. It was soon apparent, through observation of the vacuum gauge, that this frequently involved sudden appreciable throttle plate movements uncalled for by road conditions. For example, the vacuum gauge might change from 9 or 10 in. of mercury to more than 20 in. in a fraction of a second. These variations in throttle position caused significant variations in fuel consumption rates, as was demonstrated by the data collected on these early runs.

The sudden shifts in throttle position were easily explained as over-compensation by the driver for slight changes in road condition that cause momentary fluctuations in the speedometer reading. At the test site for condition 2, for example, the grade at one point (the point of curvature of a vertical curve) began reducing from +0.8 percent at a rate of 0.2 percent per 100 ft. When the vehicle arrived at this point at a given throttle setting, the driver would note a speed increase of 1 or 2 mph and immediately take his foot off the accelerator to reduce speed to that prescribed for the run. When he did this, the vehicle was likely to drop below run speed and the throttle would have to be opened an extra amount to bring the vehicle back to speed. This kind of vacillation in throttle handling caused the fuel consumption variation during early runs of the study.

The remedy was simple. For each test speed at each test site, several preliminary runs were made to establish the pattern of steady engine vacuum readings that would produce the speed required for given road conditions.

*Figure 2. Interior of test vehicle, showing accelerometer, survey speedometer, manifold vacuum gauge, and engine temperature gauge. The back of the fuelmeter is visible to the right of the driver's seat. The tachometer and part of the manifold vacuum gauge are behind the steering column.*

Then all test runs were made with the drivers adhering to this pattern of vacuum readings, ignoring sudden momentary fluctuations in the speedometer reading. The stability of the fuel consumption data collected for all succeeding test runs while adhering to this procedure proved this to be a satisfactory means of eliminating the effects of variable throttle handling.

The effects on fuel consumption values of temperature changes occurring during the course of the study, when fuel temperature varied between 70° and 110° F, were eliminated by recording fuel temperature for each trip and later adjusting each fuel reading to what it would be for a temperature of 70° F.

Most of the items of special equipment used to collect data for this study are shown with the test vehicle in Figures 2 and 3, including the accelerometer, the survey speedometer, the fuelmeter, two indicators of engine operating condition, wind measurement devices, and test weights.

## DATA ANALYSIS

The data analyses involved adjusting the fuel consumption and travel time data collected for each of the more than 4,000 test runs to arrive at values of fuel consumption (in gallons per mile at 70° F) and true speed (in miles per hour) for each uniform speed test run, and values of fuel consumption (in gallons per trip at 70° F) and time consumption (in minutes per trip) for all stop-and-go and slowdown test runs. The adjusted values were organized for graphical and tabular presentation, as described in Chapter Three.

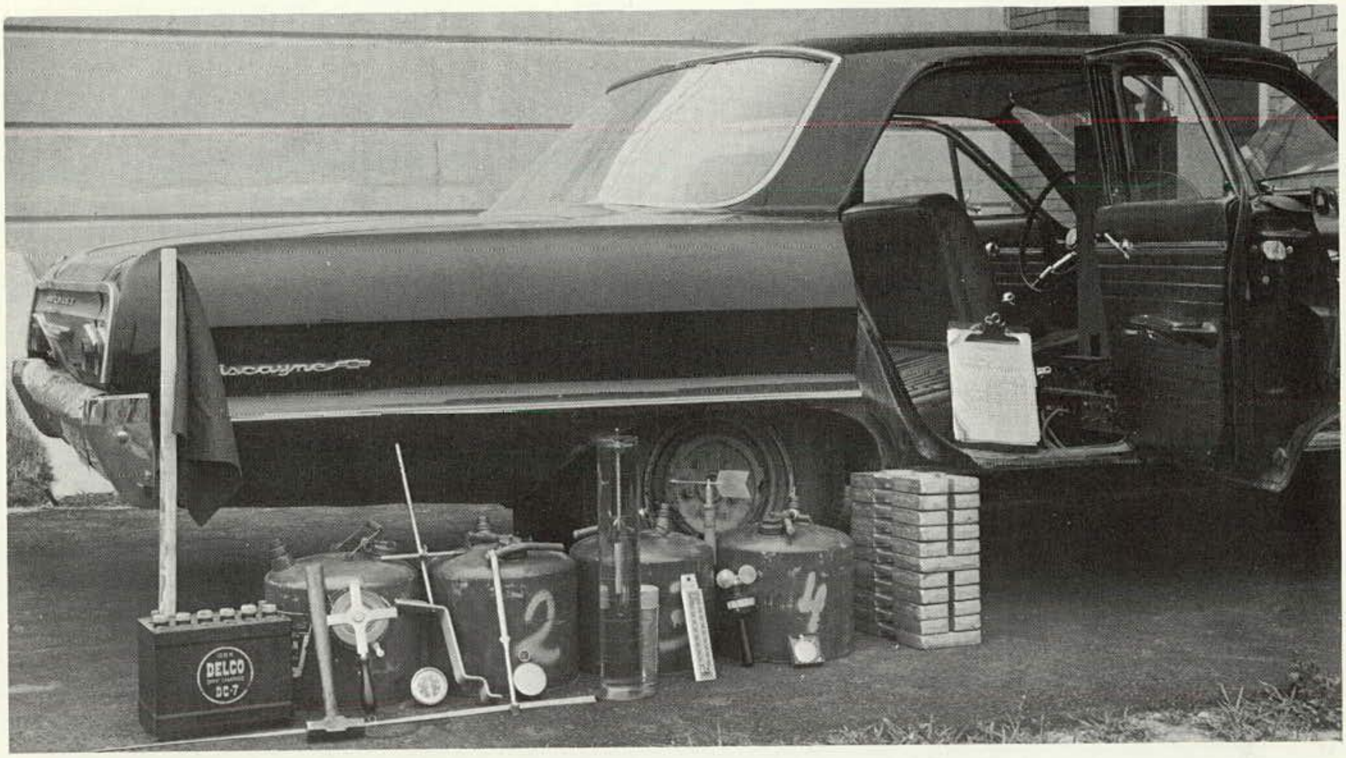

*Figure 3. Special test equipment, including hand anemometer, hand wind vane, fuel hydrometer, and weights. The front of the fuelmeter is visible at the right of the driver's seat inside the vehicle.*

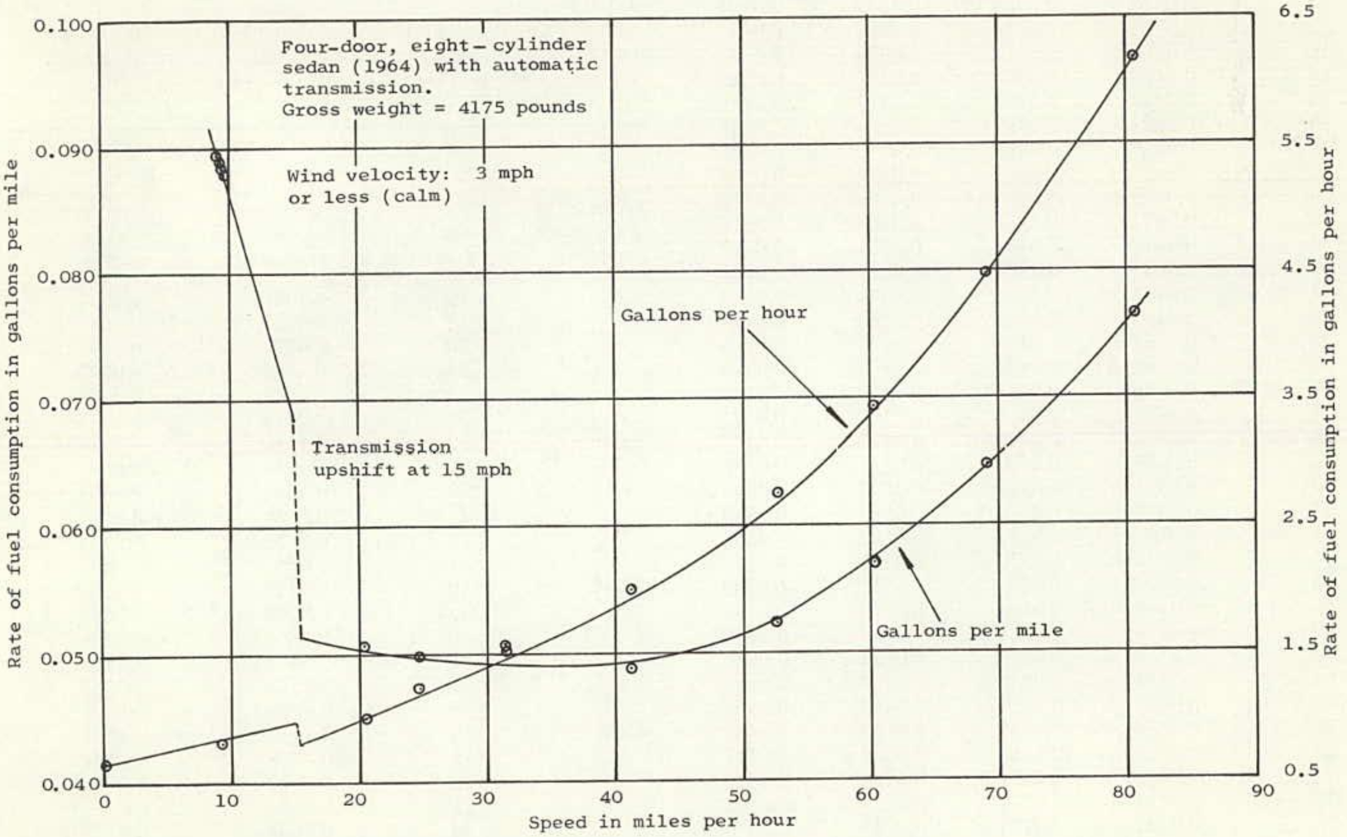

*Figure 4. Fuel consumption rates of a passenger car on a level, straight, high-type concrete pavement.*

CHAPTER THREE

# FINDINGS ON PASSENGER CAR FUEL CONSUMPTION

Figure 4 shows how the fuel consumption of the test vehicle (measured in gallons per mile and gallons per hour) varies with vehicle speed for minimum road resistance conditions (condition 1). The curves were drawn through the plotted fuel consumption values for speeds from 16 to 80 mph. For speeds below 15 mph, the speed at which the vehicle transmission upshifts, the gallons-per-mile curve was drawn as a straight line through the plotted values of fuel consumption for speeds of 8.9, 9.0, and 9.4 mph, and the gallons-per-hour curve was drawn as a straight line through the plotted values of fuel consumption for zero speed (idling in gear) and for a speed of 9.0 mph.

The assumption that the straight curve of gallons per mile through the three points in the vicinity of 10 mph can be extended as a straight line for speeds up to 14 mph results in a hiatus in the curves at the point of transmission upshift. Inasmuch as data were not collected for speeds between 10 and 14 mph it is possible that the curve should arc down from the speed of 10 mph to a direct connection with the rest of the curve for gallons per mile at 15 mph. However, although nothing was noted in the field to support this possibility, it was noticed that the engine tachometer reading dropped precipitously at the time of upshift (15 mph), indicating an abrupt change in engine operating condition at that point.

The fuel consumption rates of a passenger car operating under minimum road resistance conditions are presented in Table 1 for speeds from 8 to 80 mph in increments of

TABLE 1

FUEL CONSUMPTION ON LEVEL, STRAIGHT, HIGH-TYPE CONCRETE PAVEMENT FOR AN 8-CYLINDER 1964 SEDAN WITH AUTOMATIC TRANSMISSION (CALM WIND)

| | FUEL CONSUMPTION (GAL/MI) | | | |
|---|---|---|---|---|
| SPEED (MPH) | LOADED WEIGHT 3,600 LB | LOADED WEIGHT 4,000 LB | LOADED WEIGHT 4,400 LB | LOADED WEIGHT 4,800 LB |
| 8 | 0.0888 | 0.0918 | 0.0948 | 0.0978 |
| 10 | 0.0822 | 0.0849 | 0.0877 | 0.0904 |
| 12 | 0.0755 | 0.0780 | 0.0805 | 0.0831 |
| 14 | 0.0688 | 0.0711 | 0.0734 | 0.0757 |
| 16 | 0.0490 | 0.0507 | 0.0523 | 0.0540 |
| 18 | 0.0487 | 0.0503 | 0.0519 | 0.0536 |
| 20 | 0.0483 | 0.0499 | 0.0516 | 0.0532 |
| 22 | 0.0480 | 0.0496 | 0.0512 | 0.0528 |
| 24 | 0.0477 | 0.0493 | 0.0509 | 0.0525 |
| 26 | 0.0474 | 0.0490 | 0.0506 | 0.0522 |
| 28 | 0.0472 | 0.0488 | 0.0503 | 0.0519 |
| 30 | 0.0470 | 0.0486 | 0.0501 | 0.0517 |
| 32 | 0.0468 | 0.0484 | 0.0500 | 0.0516 |
| 34 | 0.0467 | 0.0483 | 0.0498 | 0.0514 |
| 36 | 0.0467 | 0.0483 | 0.0498 | 0.0514 |
| 38 | 0.0467 | 0.0483 | 0.0498 | 0.0514 |
| 40 | 0.0468 | 0.0484 | 0.0500 | 0.0515 |
| 42 | 0.0470 | 0.0486 | 0.0502 | 0.0518 |
| 44 | 0.0474 | 0.0490 | 0.0505 | 0.0521 |
| 46 | 0.0478 | 0.0495 | 0.0511 | 0.0527 |
| 48 | 0.0484 | 0.0500 | 0.0517 | 0.0533 |
| 50 | 0.0491 | 0.0507 | 0.0524 | 0.0540 |
| 52 | 0.0499 | 0.0516 | 0.0532 | 0.0549 |
| 54 | 0.0508 | 0.0525 | 0.0542 | 0.0559 |
| 56 | 0.0518 | 0.0535 | 0.0553 | 0.0570 |
| 58 | 0.0529 | 0.0547 | 0.0565 | 0.0583 |
| 60 | 0.0543 | 0.0561 | 0.0579 | 0.0598 |
| 62 | 0.0559 | 0.0577 | 0.0596 | 0.0615 |
| 64 | 0.0574 | 0.0594 | 0.0613 | 0.0632 |
| 66 | 0.0591 | 0.0610 | 0.0630 | 0.0650 |
| 68 | 0.0607 | 0.0628 | 0.0648 | 0.0668 |
| 70 | 0.0624 | 0.0645 | 0.0666 | 0.0687 |
| 72 | 0.0642 | 0.0664 | 0.0685 | 0.0707 |
| 74 | 0.0660 | 0.0682 | 0.0704 | 0.0726 |
| 76 | 0.0679 | 0.0702 | 0.0725 | 0.0748 |
| 78 | 0.0700 | 0.0723 | 0.0747 | 0.0770 |
| 80 | 0.0723 | 0.0747 | 0.0771 | 0.0795 |

TABLE 2

FUEL CONSUMPTION ON TWO LEVEL, STRAIGHT, LOW-TYPE ROAD SURFACES FOR AN 8-CYLINDER 1964 SEDAN WITH AUTOMATIC TRANSMISSION (CALM WIND)

| | | FUEL CONSUMPTION (GAL/MI) | |
|---|---|---|---|
| LOADED WEIGHT (LB) | SPEED (MPH) | SMOOTH SANDY-GRAVEL SURFACE | BITUMINOUS-TREATED GRAVEL SURFACE |
| 3,600 | 10 | 0.1045 | 0.1002 |
| | 15 | 0.0725 | 0.0639 |
| | 20 | 0.0620 | 0.0544 |
| | 25 | 0.0569 | 0.0500 |
| | 30 | 0.0549 | 0.0488 |
| | 35 | 0.0544 | 0.0487 |
| 4,000 | 10 | 0.1080 | 0.1035 |
| | 15 | 0.0749 | 0.0661 |
| | 20 | 0.0641 | 0.0562 |
| | 25 | 0.0588 | 0.0517 |
| | 30 | 0.0567 | 0.0505 |
| | 35 | 0.0562 | 0.0503 |
| 4,400 | 10 | 0.1115 | 0.1069 |
| | 15 | 0.0774 | 0.0683 |
| | 20 | 0.0662 | 0.0580 |
| | 25 | 0.0607 | 0.0533 |
| | 30 | 0.0585 | 0.0521 |
| | 35 | 0.0580 | 0.0519 |
| 4,800 | 10 | 0.1150 | 0.1102 |
| | 15 | 0.0798 | 0.0704 |
| | 20 | 0.0682 | 0.0598 |
| | 25 | 0.0626 | 0.0550 |
| | 30 | 0.0604 | 0.0538 |
| | 35 | 0.0598 | 0.0536 |

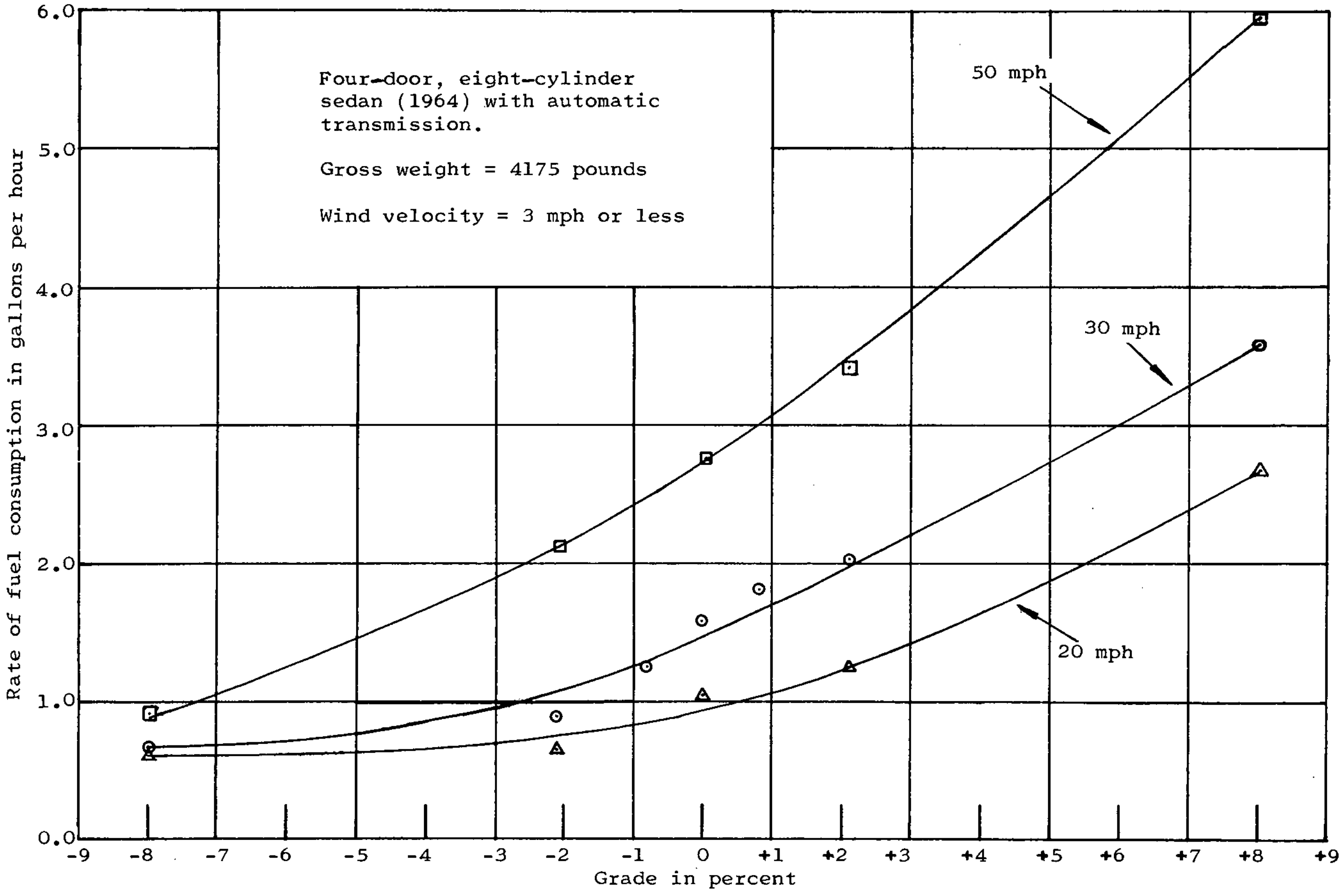

*Figure 5. Effect of road gradient on fuel consumption rate of a passenger car on a straight, high-type bituminous pavement.*

TABLE 3

FUEL CONSUMPTION ON STRAIGHT GRADES WITH HIGH-TYPE BITUMINOUS PAVEMENT FOR AN 8-CYLINDER 1964 SEDAN WEIGHING 4,000 LB LOADED, WITH AUTOMATIC TRANSMISSION (CALM WIND)

| SPEED (MPH) | FUEL CONSUMPTION (GAL/MI) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1% | 2% | 3% | 4% | 5% | 6% | 7% | 8% |
| (*a*) PLUS GRADES | | | | | | | | | |
| 15 | 0.0509 | 0.0530 | 0.0614 | 0.0718 | 0.0839 | 0.0959 | 0.1087 | 0.1219 | 0.1366 |
| 20 | 0.0500 | 0.0525 | 0.0609 | 0.0707 | 0.0818 | 0.0930 | 0.1047 | 0.1167 | 0.1298 |
| 25 | 0.0492 | 0.0520 | 0.0605 | 0.0697 | 0.0797 | 0.0901 | 0.1007 | 0.1115 | 0.1227 |
| 30 | 0.0486 | 0.0514 | 0.0600 | 0.0688 | 0.0778 | 0.0871 | 0.0967 | 0.1064 | 0.1160 |
| 35 | 0.0483 | 0.0529 | 0.0609 | 0.0691 | 0.0776 | 0.0863 | 0.0956 | 0.1053 | 0.1152 |
| 40 | 0.0484 | 0.0543 | 0.0618 | 0.0693 | 0.0774 | 0.0856 | 0.0945 | 0.1042 | 0.1145 |
| 45 | 0.0493 | 0.0557 | 0.0627 | 0.0695 | 0.0772 | 0.0849 | 0.0935 | 0.1032 | 0.1137 |
| 50 | 0.0508 | 0.0571 | 0.0634 | 0.0697 | 0.0770 | 0.0842 | 0.0925 | 0.1022 | 0.1128 |
| 55 | 0.0531 | 0.0585 | 0.0641 | 0.0699 | 0.0768 | 0.0835 | 0.0915 | 0.1012 | 0.1119 |
| 60 | 0.0562 | 0.0599 | 0.0648 | 0.0701 | 0.0766 | 0.0828 | 0.0905 | 0.1002 | 0.1101 |
| (*b*) MINUS GRADES | | | | | | | | | |
| 15 | 0.0509 | 0.0425 | 0.0389 | 0.0367 | 0.0350 | 0.0345 | 0.0335 | 0.0333 | 0.0326 |
| 20 | 0.0500 | 0.0410 | 0.0367 | 0.0340 | 0.0320 | 0.0310 | 0.0300 | 0.0295 | 0.0290 |
| 25 | 0.0492 | 0.0395 | 0.0345 | 0.0313 | 0.0290 | 0.0276 | 0.0265 | 0.0258 | 0.0254 |
| 30 | 0.0486 | 0.0380 | 0.0323 | 0.0286 | 0.0260 | 0.0241 | 0.0230 | 0.0220 | 0.0218 |
| 35 | 0.0483 | 0.0404 | 0.0347 | 0.0307 | 0.0275 | 0.0250 | 0.0231 | 0.0216 | 0.0210 |
| 40 | 0.0484 | 0.0427 | 0.0372 | 0.0328 | 0.0290 | 0.0258 | 0.0233 | 0.0213 | 0.0201 |
| 45 | 0.0493 | 0.0450 | 0.0396 | 0.0348 | 0.0304 | 0.0267 | 0.0234 | 0.0209 | 0.0193 |
| 50 | 0.0508 | 0.0474 | 0.0420 | 0.0369 | 0.0319 | 0.0275 | 0.0235 | 0.0205 | 0.0184 |
| 55 | 0.0531 | 0.0498 | 0.0444 | 0.0390 | 0.0334 | 0.0284 | 0.0236 | 0.0201 | 0.0176 |
| 60 | 0.0562 | 0.0521 | 0.0469 | 0.0411 | 0.0349 | 0.0292 | 0.0238 | 0.0198 | 0.0167 |

TABLE 4

FUEL CONSUMPTION FOR DECELERATING FROM AN INITIAL SPEED TO STOP, OR TO A LOWER SPEED, AND IMMEDIATELY ACCELERATING BACK TO THE INITIAL SPEED, IN EXCESS OF THAT FOR CONTINUING AT THE INITIAL SPEED FOR AN 8-CYLINDER 1964 SEDAN WEIGHING 4,000 LB LOADED, WITH AUTOMATIC TRANSMISSION (SPEED CHANGES AT 5 FT/SEC/SEC, EXCEPT ACCELERATION ABOVE 30 MPH AT 2.5 FT/SEC/SEC)

| INITIAL SPEED (MPH) | ADDITIONAL FUEL CONSUMPTION (GAL/CYCLE) FOR LOWER SPEED OF | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | STOP | 5 MPH | 10 MPH | 15 MPH | 20 MPH | 25 MPH | 30 MPH | 35 MPH | 40 MPH | 45 MPH | 50 MPH | 55 MPH | 60 MPH |
| 5 | 0.00038 | 0 | — | — | — | — | — | — | — | — | — | — | — |
| 10 | 0.00180 | 0.00101 | 0 | — | — | — | — | — | — | — | — | — | — |
| 15 | 0.00320 | 0.00241 | 0.00142 | 0 | — | — | — | — | — | — | — | — | — |
| 20 | 0.00462 | 0.00381 | 0.00292 | 0.00179 | 0 | — | — | — | — | — | — | — | — |
| 25 | 0.00601 | 0.00530 | 0.00441 | 0.00344 | 0.00220 | 0 | — | — | — | — | — | — | — |
| 30 | 0.00743 | 0.00673 | 0.00594 | 0.00504 | 0.00397 | 0.00262 | 0 | — | — | — | — | — | — |
| 35 | 0.00885 | 0.00794 | 0.00702 | 0.00608 | 0.00504 | 0.00384 | 0.00247 | 0 | — | — | — | — | — |
| 40 | 0.01027 | 0.00927 | 0.00825 | 0.00716 | 0.00605 | 0.00492 | 0.00361 | 0.00210 | 0 | — | — | — | — |
| 45 | 0.01168 | 0.01072 | 0.00971 | 0.00867 | 0.00758 | 0.00646 | 0.00532 | 0.00398 | 0.00246 | 0 | — | — | — |
| 50 | 0.01311 | 0.01214 | 0.01119 | 0.01016 | 0.00913 | 0.00808 | 0.00697 | 0.00580 | 0.00446 | 0.00291 | 0 | — | — |
| 55 | 0.01452 | 0.01355 | 0.01254 | 0.01150 | 0.01045 | 0.00936 | 0.00825 | 0.00707 | 0.00590 | 0.00456 | 0.00293 | 0 | — |
| 60 | 0.01596 | 0.01495 | 0.01395 | 0.01290 | 0.01182 | 0.01072 | 0.00958 | 0.00838 | 0.00714 | 0.00591 | 0.00448 | 0.00281 | 0 |

TABLE 5

TIME CONSUMPTION FOR DECELERATING FROM AN INITIAL SPEED TO STOP, OR TO A LOWER SPEED, AND IMMEDIATELY ACCELERATING BACK TO THE INITIAL SPEED, IN EXCESS OF THAT FOR CONTINUING AT THE INITIAL SPEED FOR AN 8-CYLINDER 1964 SEDAN WEIGHING 4,000 LB LOADED, WITH AUTOMATIC TRANSMISSION (SPEED CHANGES AT 5 FT/SEC/SEC, EXCEPT ACCELERATION ABOVE 30 MPH AT 2.5 FT/SEC/SEC)

| INITIAL SPEED (MPH) | ADDITIONAL TIME CONSUMPTION (MIN/CYCLE) FOR LOWER SPEED OF | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | STOP | 5 MPH | 10 MPH | 15 MPH | 20 MPH | 25 MPH | 30 MPH | 35 MPH | 40 MPH | 45 MPH | 50 MPH | 55 MPH | 60 MPH |
| 5 | 0.0533 | 0 | — | — | — | — | — | — | — | — | — | — | — |
| 10 | 0.0801 | 0.0294 | 0 | — | — | — | — | — | — | — | — | — | — |
| 15 | 0.1064 | 0.0522 | 0.0200 | 0 | — | — | — | — | — | — | — | — | — |
| 20 | 0.1330 | 0.0746 | 0.0418 | 0.0179 | 0 | — | — | — | — | — | — | — | — |
| 25 | 0.1596 | 0.1054 | 0.0677 | 0.0377 | 0.0152 | 0 | — | — | — | — | — | — | — |
| 30 | 0.1857 | 0.1406 | 0.0984 | 0.0627 | 0.0347 | 0.0142 | 0 | — | — | — | — | — | — |
| 35 | 0.2118 | 0.1634 | 0.1168 | 0.0795 | 0.0489 | 0.0260 | 0.0095 | 0 | — | — | — | — | — |
| 40 | 0.2384 | 0.1846 | 0.1385 | 0.0978 | 0.0636 | 0.0380 | 0.0180 | 0.0052 | 0 | — | — | — | — |
| 45 | 0.2641 | 0.2180 | 0.1734 | 0.1311 | 0.0939 | 0.0636 | 0.0390 | 0.0200 | 0.0066 | 0 | — | — | — |
| 50 | 0.2905 | 0.2529 | 0.2054 | 0.1647 | 0.1264 | 0.0920 | 0.0627 | 0.0385 | 0.0190 | 0.0057 | 0 | — | — |
| 55 | 0.3164 | 0.2733 | 0.2280 | 0.1862 | 0.1487 | 0.1121 | 0.0809 | 0.0536 | 0.0309 | 0.0147 | 0.0043 | 0 | — |
| 60 | 0.3420 | 0.2926 | 0.2518 | 0.2112 | 0.1700 | 0.1323 | 0.0974 | 0.0657 | 0.0416 | 0.0247 | 0.0117 | 0.0032 | 0 |

2 mph, and for loaded weights of 3,600, 4,000, 4,400, and 4,800 lb. The values were taken from Figure 4, adjusted for vehicle weight as explained in Chapter Four.

Table 2 gives fuel consumption rates for each of four loaded passenger car weights for operation on (a) a smooth loose-textured sandy-gravel road surface, and (b) a bituminous-treated gravel surface.

Figure 5 shows the relationship between the fuel consumption rate of the test vehicle in gallons per hour and highway grades varying in slope from —0.8 percent to +0.8 percent. The plotted points fall closely along smooth curves. It should be noted that fuel consumption rates are reduced to those for idling in gear (0.66 gal per hr) for both the 20-mph and the 30-mph speeds when operation is on a —0.8 percent grade.

Fuel consumption rates for operation of a 4,000-lb passenger car on various grades are given in Table 3.

The fuel consumption and time consumption of a passenger car for vehicle stops and slowdowns in excess of fuel and time consumption over uniform speed operation are given in Tables 4 (fuel) and 5 (time). These values were measured by operating the test vehicle through a series of speed-change cycles at each of six running (initial) speeds: 10, 20, 30, 40, 50, and 60 mph. Each speed-change cycle involved reducing from the running or initial speed to stop or to a lower speed at a deceleration rate of 5 ft/sec/sec, and immediately accelerating back to the initial speed at a rate of 5 ft/sec/sec for speeds from 0 to 30 mph, and at a rate of 2.5 ft/sec/sec for speeds above 30 mph. Slowdown cycles were made for speed reductions of 10, 20, 30, and 40 mph.

The fuel consumption of the test vehicle for operation on curves was investigated for a curve with 65-ft radius and another with 955-ft radius (6°), both laid out on a taxiway at Bolling Air Force Base, Washington, D. C. As previously described, this provided a level paved surface, with the 65-ft radius curve as a circle, and the 955-ft radius curve as a 1,000-ft arc with tangents at each end running off on paved runways intersecting the taxiway. A straight 1,000-ft test section was also prepared at the same location so that comparison runs on straight alignment could be made.

More than 30 test runs of 3,100 ft each (7.6 times around the full circumference) were made on the 65-ft radius circle at 20 mph. Fuel consumption for this type of operation was found to be 0.1044 gal per mile, approximately double that for operation on straight alignment.

More than 30 test runs were also made on the 1,000-ft arc of the 955-ft radius curve and on the straight 1,000-ft comparison section at 30 mph for calm wind conditions. The fuel consumption rate on this curve was found to be 0.0560 gal per mile and on the straight section 0.0523 gal per mile, an additional 0.0037 gal per mile for operation on the curve. Thus, fuel consumption for a level 955-ft radius curve at 30 mph is about 7 percent more than that for operation at this same speed on straight alignment.

The fuel consumption rates of the test vehicle while idling at stop (a) with transmission in neutral and engine speed at 850 rpm, and (b) with transmission in drive and engine speed at 650 rpm, were found to be 0.65 and 0.66 gal per hour, respectively.

CHAPTER FOUR

# APPRAISAL OF FINDINGS

The most important consideration governing the planning of this project, the development of data collection and analysis procedures, and the presentation of results, has been to assure the accuracy of these results. A study of this nature is nearly useless if it is lacking in accuracy, or even if its accuracy is questioned. The unit fuel costs for individual passenger car operation are of a small order, a few cents per mile, but these will be multiplied by the planner by tens of thousands of cars to arrive at the total fuel cost for the large populations of vehicles that will use a particular road or section of road during a period of time. Minute errors in the unit costs of passenger car operation will be magnified into many thousands of dollars of error in the determination of total highway user costs by the planner. Accuracy in the measurement of the unit operating costs must be assured.

A second consideration, strongly affecting the planning of this project, is the importance of developing motor vehicle cost information for explicit highway and traffic conditions in such a way that transportation planners can extend basic cost values from research reports such as this to cover a wider variety of conditions than those shown in the report. For example, if data on vehicle operating costs for operation on various grades are available, along with data on vehicle costs for operation on each of several different road surfaces at zero grade, the planner should be able to determine the combined cost for operation on a given combination of grade and surface condition even though specific cost measurements for the combined condition have not been made.

## ACCURACY CONSIDERATIONS

Aside from the care exercised in the choice of test sites (see Chapter Two) and the service capability developed in the fuelmeter (see Appendix B), the primary means of assuring the accuracy of the fuel measurements were frequent determinations of engine performance characteristics, careful control of the fuel supply, and the use of vehicle operation techniques that eliminate the effects of a series of different drivers during the data collection period.

Engine performance characteristics were determined by placing the vehicle on a dynamometer and attaching an exhaust gas analyzer. The dynamometer made it possible to operate the vehicle at various speeds and at various loads while the engine manifold vacuum and the air-fuel ratio of the exhaust gases were measured. Plotting air-fuel ratios versus engine vacuum gave a typical pattern of engine performance for assessing the consistency in the engine's efficiency in the use of fuel.

Three dynamometer air-fuel ratio tests were made on the test vehicle—at the beginning, the mid-point, and the end of the test period. The pattern of engine performance was substantially the same for all three determinations, assuring that the vehicle's engine operating condition remained consistently good throughout the test.

A well-known brand of regular grade gasoline was used throughout the test. It was obtained from the University supply, which during the course of the field tests was replenished twice. Thus, fuel from three different deliveries by the supplier was used for the fuel consumption measurements.

Special test runs were made to determine the effect on fuel consumption rates of using fuel from two different supplies. Duplicate series of test runs were made at 30, 40, and 60 mph, using for one series the fuel originally in the supply tank and for the other series fuel from the first delivery by the supplier after the test began (Fig. 6).

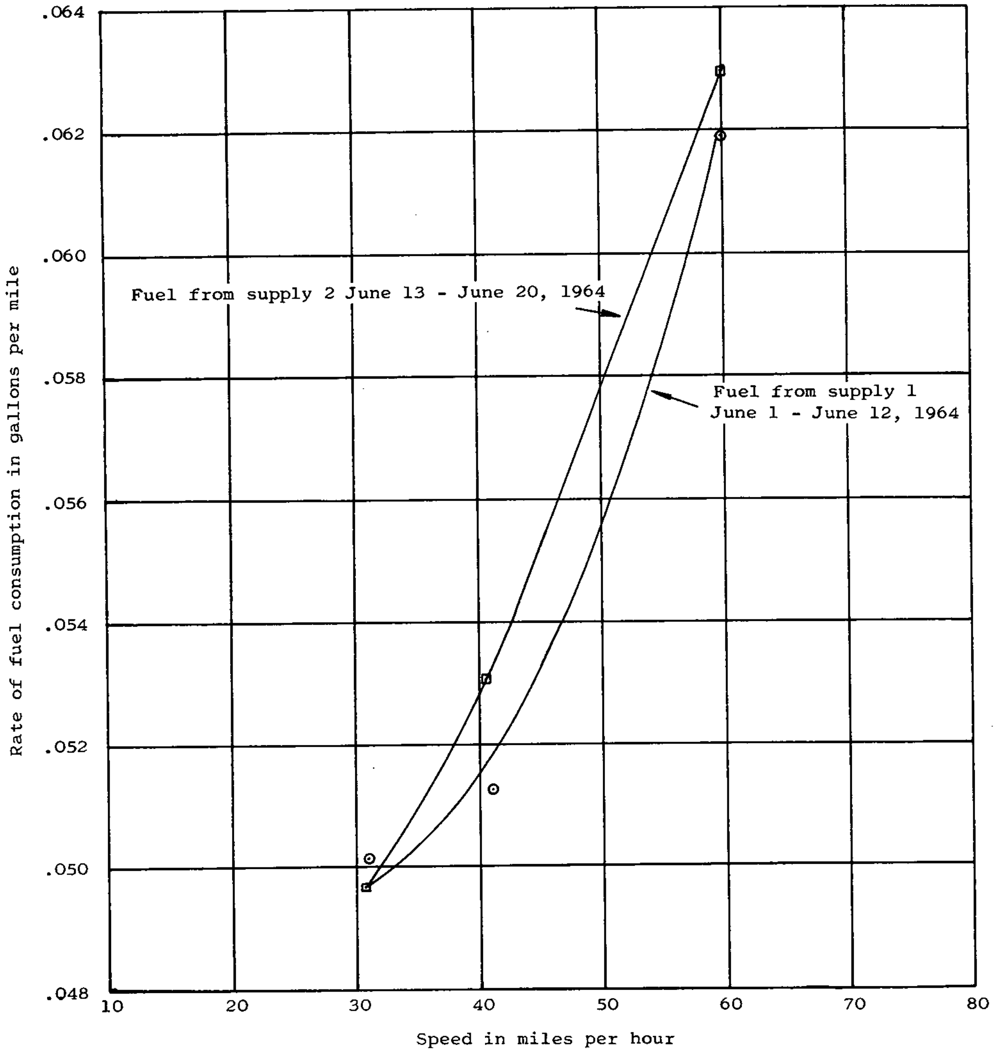

*Figure 6. Effect on passenger car fuel consumption rate of using fuel from two different supplies of the same grade and brand of fuel (on level high-type pavement).*

At 30 and 60 mph the total variation is less than 2 percent, although at 40 mph it becomes 3 percent. Thus, there is a possible error from a mean of 1 to 2 percent when fuels from different supplies are used. This error was minimized by having all runs included for any particular test condition made using fuel from the same supply.

Special test runs were also made early in the test period to determine the variability in fuel consumption data arising as a result of variation in the drivers' throttle manipulation techniques. Figure 7 shows how average fuel consumption rates differed among drivers for test runs at speeds of 25, 30, and 40 mph with test conditions identical for each run, including use of fuel from the same supply. Total variation was on the order of 3 percent.

The variations in fuel consumption rates due to differences in throttle manipulation techniques noted in Figure 7 resulted from the tendency of the drivers to overcompensate for small momentary changes in speedometer readings when they attempted to maintain a particular speedometer reading. These variations were almost entirely eliminated by instituting a procedure whereby a series of preliminary runs was made over each test section at each speed before actual test runs were begun, in order to establish the pattern of manifold vacuum readings necessary to sustain given speeds for a particular site. Then all test runs were made by observing vacuum readings rather than speedometer readings and by driving so as to maintain these readings according to the pattern established by the preliminary runs.

An important verification of the accuracy of the fuel consumption measurements made for this study was accomplished by making a series of runs at a special test site where two of the road conditions being investigated in this study existed at one location. The average fuel consumption rate determined for operation at this site should equal the sum of the fuel consumption rate for minimum road resistance conditions (flat, level, high-type pavement) plus the sum of the increments of fuel consumption rate due to each of the two special road conditions at the site.

The special test site selected for this purpose was a sandy-gravel section of the road now in use where the westbound lanes of the Suitland Parkway near Morningside, Md., will eventually be constructed. The section has an average grade of 1.75 percent, being 1 percent for a quarter of its length and 2 percent for the remainder.

The average fuel consumption rate at this site was determined to be 0.0730 gal per mile after 30 test runs at 20 mph in the upgrade direction. This is almost equal to the synthesized rate of 0.0720 gal per mile for 20-mph speeds, determined as follows:

Fuel consumption rate on level paved road at 20 mph (Fig. 4) . . . . . . . . . . . . . . . . = 0.0505 gal/mi
Incremental fuel consumption rate for operation on 1.75 percent grade rather than level grade at 20 mph (Fig. 5 — Fig. 4) . . . . . . . . . . . . . . . . . . . . . . . = 0.0070 gal/mi
Incremental fuel consumption rate for operation on sandy-gravel road rather than on paved road at 20 mph (Table 3 * — Fig. 4) . . . . . . . . . . . . . . . . . . . = 0.0145 gal/mi

Total . . . . . . . . . . . . . . . . . . . . . . . . . . . = 0.0720 gal/mi

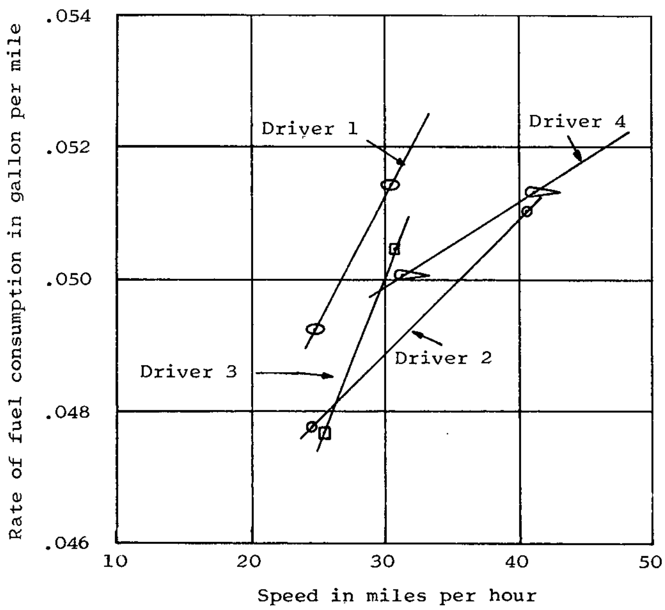

*Figure 7. Effect on passenger car fuel consumption rate of differences in driver performance for four carefully trained drivers (on level high-type pavement).*

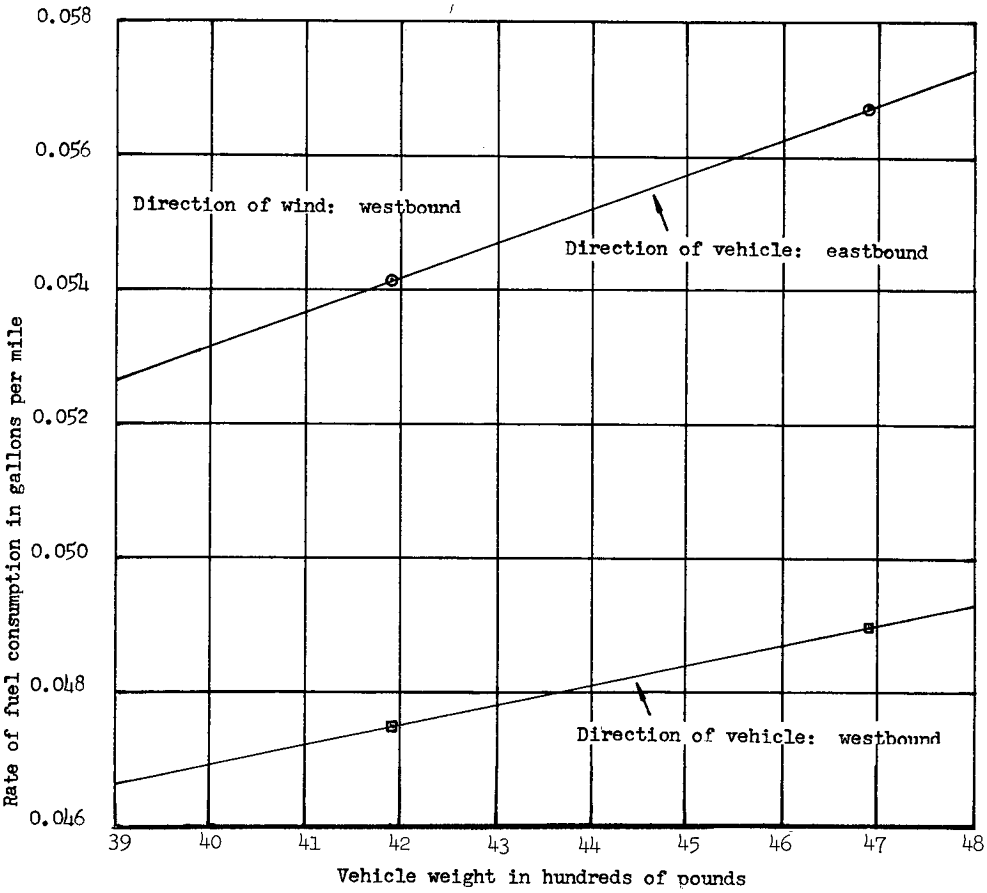

*Figure 8. Effect on passenger car fuel consumption rate of different gross vehicle weights for operation on a level high-type pavement at 40 mph with 8-mph wind acting parallel to vehicle motion.*

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* Tabular value for 4,000-lb weight must be increased at a rate of 8 percent per additional 1,000 lb to adjust to the weight of 4,175 lb.

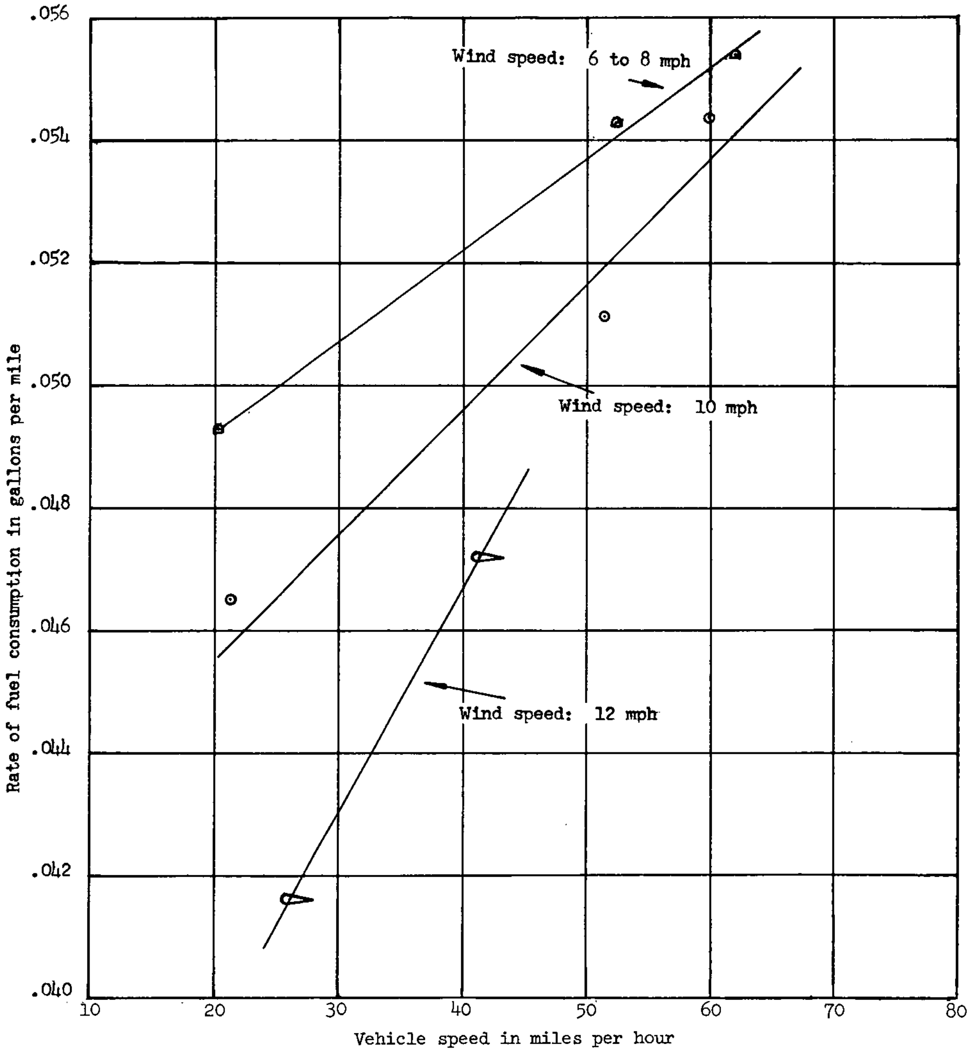

*Figure 9. Effect on passenger car fuel consumption rate of parallel eastbound winds when vehicle is eastbound (on level high-type pavement).*

The close agreement between the fuel consumption rate for a given set of road conditions obtained by direct measurements and the rate found by synthesizing fuel consumption data for the individual highway factors making up the particular road conditions, constitutes an overall verification of both the accuracy and the precision of the study results.

## EXTENSION OF STUDY RESULTS

The results of this study can be used to determine motor vehicle costs for numerous operating conditions in addition to those for which data are given in Chapter Three. The results can be extended to give fuel cost for loaded vehicle weights other than those for which data are listed, for operation under various wind conditions, and for operation on roads where two or more different road conditions are found at the same location.

Figure 8 shows how the fuel consumption of a passenger car varies with gross vehicle weight for operation on a straight level road under identical road conditions, wind velocities and operating speed. The upper curve gives results for operations into the wind and the lower curve for operation with the wind, but the slope of the curve is nearly the same in each case. The average increase in passenger car fuel consumption rates for operation on level straight roads is 8 percent per 1,000 lb of increase in weight.

The fuel consumption rates during acceleration for standard 8-cylinder passenger cars of different gross weights are directly proportional to vehicle weight as long as the acceleration rate is the same.

Figures 9 and 10 show the effect on passenger car fuel consumption rates of winds acting parallel to the motion of a vehicle. The fuel consumption of 6- to 8-mph winds is higher at lower speeds when moving with the wind than when moving against the wind, with the effect being reversed at speeds above 45 mph, indicating that the

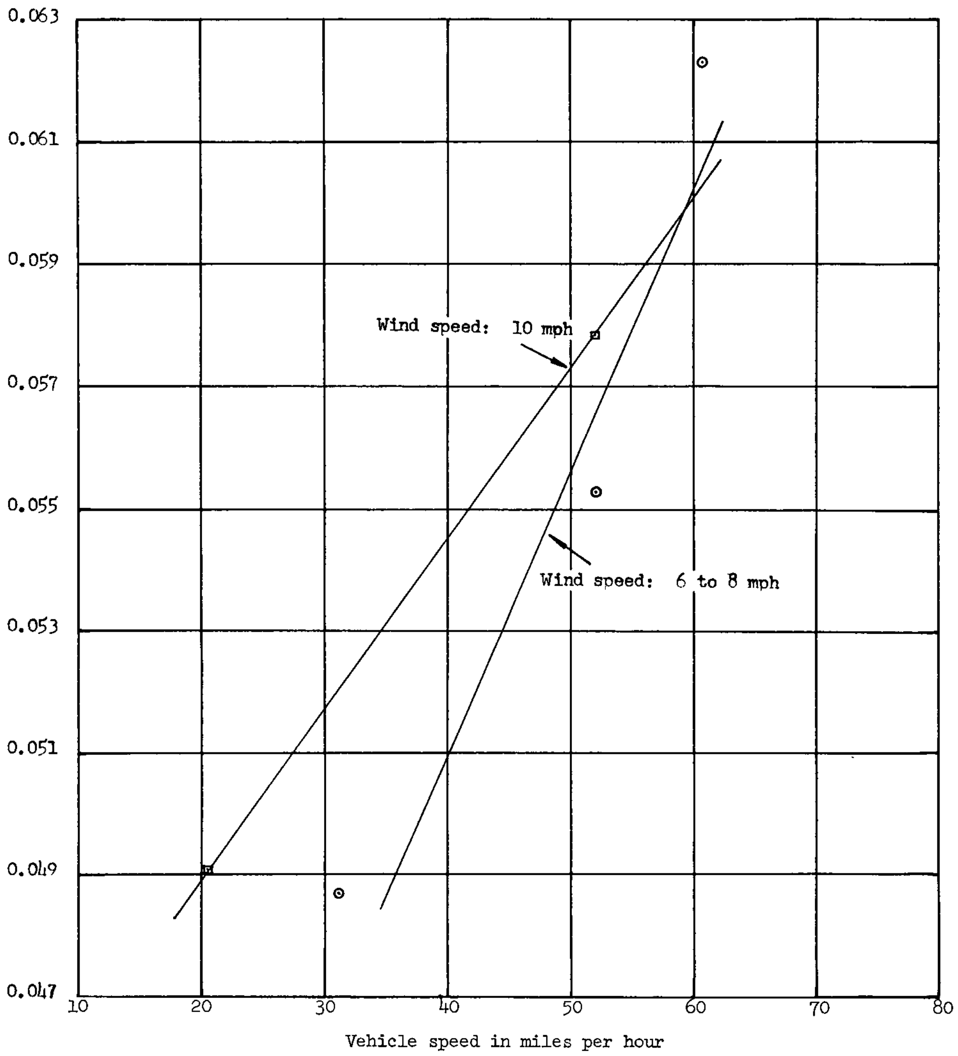

*Figure 10. Effect on passenger car fuel consumption rate of parallel eastbound winds when vehicle is westbound (on level high-type pavement).*

effect of wind on vehicle fuel consumption at the lower speeds is not of significance for wind speeds below 8 mph.

Winds of 10 mph, however, cause significantly higher fuel consumption rates when directed against the motion of a vehicle (Fig. 10) than when moving with the vehicle (Fig. 9), and a wind of 12 mph causes an appreciable reduction in fuel consumption when wind and vehicle motion are in the same direction.

It is possible to estimate the additional fuel consumption due to the effects of 10- and 12-mph winds by subtracting from the values shown in Figures 9 and 10 the corresponding fuel consumption values of Figure 4 (calm wind). This can be of importance in estimating fuel consumption rates in tunnels, deep cuts, and downtown metropolitan streets where moving air tends to be channeled along the path of vehicle movement.

The most significant manner by which the findings of this report can be extended, however, is by combining incremental fuel consumption rates of passenger cars for different basic road conditions to determine fuel consumption rates for operation on roads when two or more of these road conditions exist at one location.

# APPENDIX A

## ANNOTATED BIBLIOGRAPHY OF HIGHWAY MOTOR VEHICLE OPERATING COSTS, 1948-1962

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## II. FUEL CONSUMPTION

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## III. TIRE WEAR

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## V. MAINTENANCE

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## VI. DEPRECIATION

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# APPENDIX B

## PHOTO-ELECTRONIC FUELMETER* FOR MOTOR VEHICLE OPERATING COST STUDIES

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The measurement of fuel consumption of passenger cars and commercial vehicles is not new, but the need to keep abreast of vehicle and highway improvements has created a demand for a very precise fuel measuring device. The highway engineer has been only partially informed of the limitations of the motor vehicle in the design of modern highways. There is mounting evidence that the most satisfactory solution to the economics of motor vehicle transportation is a compromise between highway and vehicle design. Future highways should be designed with the aid of the most precise information concerning the operating characteristics of the motor vehicle. Length of highway, magnitude of grades, amount of road curvature, speed changes and roadway surfaces are some of the items that influence vehicle running costs.

Probably the greatest single drawback to obtaining precise fuel consumption data has been the lack of a reliable precision fuelmeter capable of performing properly under a wide variety of vehicle and road conditions. It is the purpose of this paper to describe a fuelmeter that will satisfy this need, thereby providing a means for accumulating the type of data that will assist in improving vehicle and highway design.

### OTHER TYPES OF FUELMETERS

A review of the literature reveals that precision fuelmeters which have been used for measuring fuel consumption of motor vehicles fall into one of two general categories—the buret type (*4, 10, 11, 12*) and the volumetric positive displacement type (*2, 4, 5, 6, 8, 11, 13*). The buret type consists of a bank of calibrated glass tubes which are filled from the vehicle's fuel tank through tubing and valves. In like manner, the fuel is permitted to flow to the vehicle's carburetor through tubing and valves. An observer in the test vehicle manually operates the valves to allow passage of fuel from only the burets during travel over a test section of a highway. To keep the amount of valve manipulation to a minimum, burets having a large fuel capacity (2 to 3 in. in diameter) are used. Consequently, there is a great deal of sloshing of fuel in the burets, making it necessary to stop the vehicle each time a reading of the fuel surface level has to be made. Despite the size of the burets, operators frequently forget to close a valve during the filling cycle of a buret and overflowing results. Even if the operator stops the filling operation before the fuel overflows, it nullifies a test run if the fuel is allowed to rise above the true fill mark location. These difficulties, plus the problem of fuel odor and fumes from the large burets, have led most investigators of vehicle fuel consumption to avoid the buret system of fuel measurements.

The need for a more convenient means of measuring fuel consumption for motor vehicle operating cost studies led to development of the volumetric positive-displacement type of fuelmeter, like the Petrometa (*6, 11*). This type of meter operates on the principle of displacement and consists of several pistons which actuate a crankshaft and slide valves. Each operation of the crankshaft actuates an associated counting mechanism, which indicates multiples of the amount of fuel displaced by the pistons. The precision of such fuelmeters has been reported as being to the nearest 0.05 gal (*2*). However, calibration has been found to be difficult (*11*), as the calibration factor varies for different flow rates and is sensitive to fuel pump pressure, temperature, and battery voltage. This type of meter is very sensitive to heat and, when used for any appreciable length of time, particularly in warm weather, will fail either by stopping the flow of fuel entirely or by giving erratic results. An attempt has been made to remedy some of the shortcomings of the positive-displacement type of meter by employing compressed air to operate the valves (*13*), but success of this approach has not been recorded in the literature.

The photo-electronic fuelmeter was developed to meet the need for a dependably accurate and precise meter for measuring motor vehicle fuel consumption for highway user cost studies. It is designed for convenient and dependable service for all operating conditions encountered on modern highways.

### BURET METHOD OF FUEL CONSUMPTION

Buret systems measure the amount of fuel used by an engine by measuring the difference in level of the fuel in the buret as it flows from the buret to the engine. It is a simple and direct means of measuring fuel consumption and of such assured accuracy that it is often used to calibrate other types of fuelmeters.

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* All patent rights reserved by the author subject to the license rights of the U. S. Government as provided in Amendment No. 1 of National Cooperative Highway Research Program Contract HR-63-2-5 dated July 17, 1963.

However, buret systems for fuel consumption meters have always involved not only manual operation of the valves controlling the flow of fuel to the tubes and from the tubes to the engine, but also direct visual observation of graduations on the buret to obtain volume change of fuel. There also were the several disadvantages mentioned in the previous section.

### PHOTO-ELECTRONIC FUELMETER

The photo-electronic fuelmeter, retaining the advantages of the buret system for accurate, precise, and dependable service, provides an electronic means both for automatically operating the valves controlling the fuel flow into and out of the tubes, and for detecting and presenting as simple digital readings actual fuel consumption information. This is accomplished by means of photo-electronic cells and associated light sources which are able to detect the level of the fuel surface in the tubes at critical points. The opening and closing of valves can therefore be programmed for particular positions of the fuel surfaces in the tubes and the graduated buret readings of fuel consumption can be automatically registered on a dial by electrical pulsations.

### DESIGN DETAILS

The precision photo-electronic fuelmeter consists of a battery of three graduated 100-cc burets housed in lighttight cases, six electrically controlled fuel valves, and the several electronic devices as shown in Figure B-1. Fuel is pumped into the burets through valves $A_2$, $B_2$, and $C_2$ and drawn out of the burets by the fuel pump to the engine through valves $A_1$, $B_1$, and $C_1$. Photo-conductive cells are set opposite light sources at each 5-cc point of each buret (Fig. B-2). The meter measures and records each 5 cc of fuel as it is taken from each buret in sequence.

The drain and refill valves are opened and closed electrically in proper sequence by the programmer switch in chassis No. 2, which in turn is operated by electrical impulses received from the stepper switch in chassis No. 1 (Fig. B-1). The stepper switch responds to the position of the fuel surface in each buret as fuel is withdrawn. Detection of the position of the fuel surface is accomplished by means of the photo-conductive cells mounted at right angles to the tube at the 5-cc graduations on each buret as previously noted. A photo-cell at the top of each tube detects when the tube is properly filled during the filling portion of the operation cycle and causes the closing of the associated refill valve.

In operation, an opaque float on the surface of the column of fuel in a given buret moves down as fuel is withdrawn by the engine. In doing so it interrupts the light source opposite the photo-conductive cell at each 5-cc point. At each interruption of a light beam an electric relay is actuated through an electronic amplifier, which in turn actuates an impulse counter that counts the interruptions. The counter indication is a count of the number of these interruptions at any time and is the fuel consumption reading to the nearest 5 cc. There are 20 counts for each 100-cc buret.

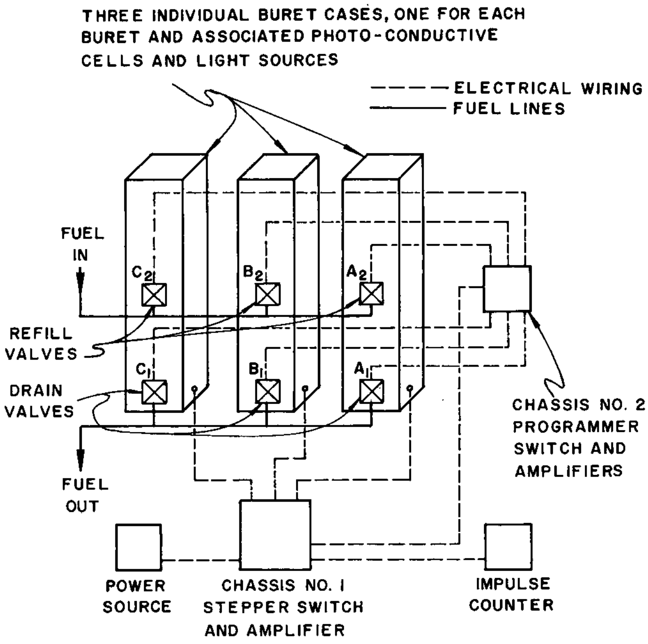

*Figure B-1. Block diagram of photo-electronic fuelmeter.*

Each interruption of a light beam not only actuates the counter through the amplifier and relay, but also energizes a stepper coil, which advances the stepper switch (Fig. B-1). The 20 photo-conductive cells are so connected to this stepper switch that only one cell, specifically the one positioned in advance of the moving float, is connected to the amplifier and relay circuit.

The 20 photo-conductive cells of each buret are connected as a group to each of three stages of the stepper switch. The contacting wiper of each of the three stages of the stepper switch is connected separately to an off-on switch in the programmer switch (Fig. B-3). Thus, because only one of the three programmer off-on wiper switches can be in the "on" position at any one time, the counting procedure can take place in only one buret at any one time.

In addition to the three counting stages, the stepper switch has a fourth stage (stepper D, Fig. B-2) which energizes the coil of the programmer switch when the last (lowest) light beam in any one buret is interrupted. The programming switch contains an electrical solenoid-operated cam and three sets of off-on switches. These switches control both the proper selection of the stepper stage and the opening and closing of the refill and drain valves. Thus, as the last light interruption occurs in any one buret (for example, buret C) the following operations take place simultaneously: (1) wiper of stepper stage A is connected to the amplifier and relay circuit in order to initiate the counting process in buret A, (2) drain valve $C_1$ closes, (3) drain valve $A_1$ opens, and (4) refill valve $C_2$ opens. All other valves remain closed (Fig. B-3).

Thus, as the last 5-cc unit of fuel in buret C has been counted, the draining and counting function is transferred

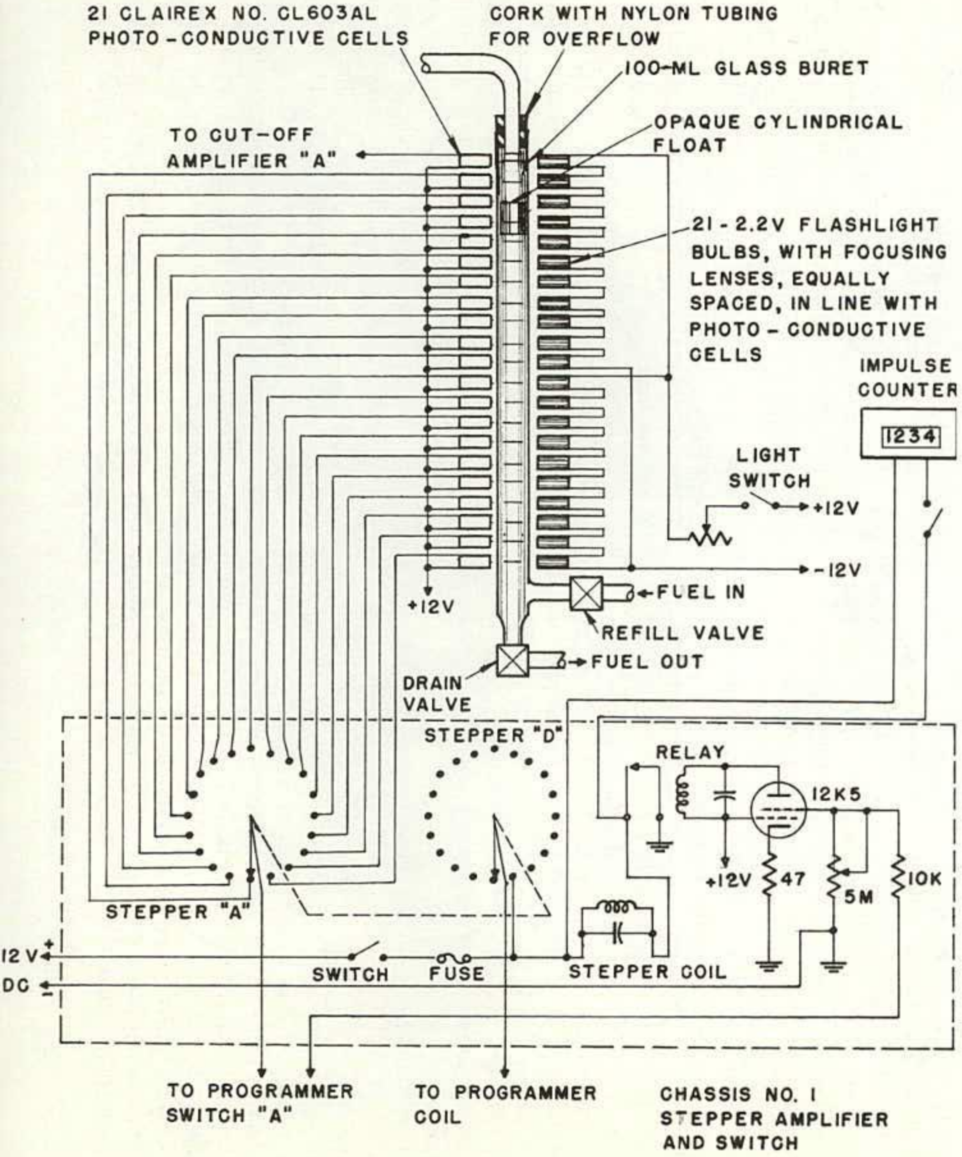

*Figure B-2. Typical buret wiring and associated circuitry.*

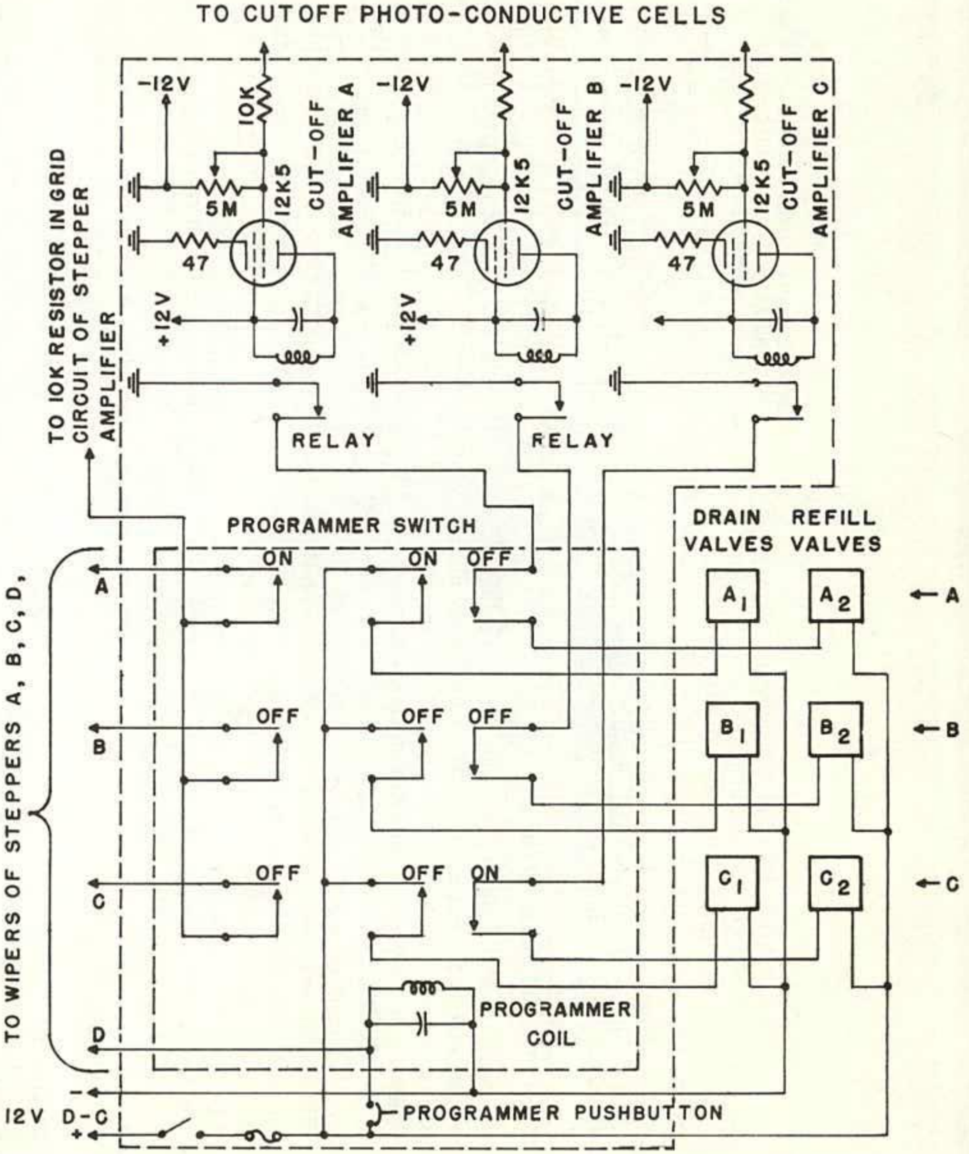

*Figure B-3. Programmer switch and associated circuitry.*

from buret C to buret A and the refill valve for buret C is opened. The refilling process will stop automatically when the float interrupts the light beam directed on the topmost, or cutoff, photo-conductive cell as this electrically actuates an electric relay in the cutoff amplifier circuit that closes the refill valve. Buret C will remain filled until the counting process again takes place in buret C. The refilling operation functions independently of the counting operation.

The process described for the draining and counting of fuel in buret C, the transfer of operations to buret A, and the refilling of buret C, is repeated for each buret in sequence with corresponding changes in the positions of the drain and refill valves and in the connections from buret C to buret A, to buret B, to buret C, and so on. The process will continue indefinitely as long as fuel is available and is being used. Specifically, the positions of the various switches in the programmer are arranged in the following manner as the counting process is transferred from buret to buret:

| | Wiper Switch | Drain Valve Switch | Refill Valve Switch |
|---|---|---|---|
| 1. *Counting in buret A* | | | |
| A. | On | On | Off |
| B. | Off | Off | Off |
| C. | Off | Off | On |
| 2. *Counting in buret B* | | | |
| A. | Off | Off | On |
| B. | On | On | Off |
| C. | Off | Off | Off |
| 3. *Counting in buret C* | | | |
| A. | Off | Off | Off |
| B. | Off | Off | On |
| C. | On | On | Off |

Front and rear views of the fuelmeter are shown in Figure B-4.

## INSTALLATION AND OPERATION

The buret cases and accessory chassis of the photo-electronic fuelmeter may be located in a vehicle wherever it is most convenient for the observer, subject only to the stipulation that the buret cases be mounted in an upright position. Because the only connections between the buret cases and chassis 1 and 2 are long flexible electrical cables, each may be located in a separate place in the vehicle. For example, in an automobile the burets may be set up on the floor behind the front seat while the two chassis are mounted in the trunk. Only the small impulse counter box need be in front near the observer. The intake line of the burets is connected to the fuel tank through an electric pump mounted permanently on the buret boxes. The output line of the burets is connected directly to the input of the vehicle's regular fuel pump. It is convenient to install a bypass system to divert fuel past the meter when operation of the meter is not necessary.

A conventional 12-v automobile battery provides the necessary electrical energy to operate the system. Voltage impressed on the meter must fall between 11.5 and 12.5 v for the meter to function. Normally, the meter will operate continuously for 4 hr before a newly charged battery will need recharging. When the voltage drops below a critical value, the meter will completely stop. This is an important feature, inasmuch as it guarantees that the meter will not continue to operate giving erroneous data after its power supply is reduced below some critical level.

Operation is extremely simple. Three steps are required to start the meter. First, three switches are turned on to activate the circuitry for each of the three burets. Second, the fuel pump switch is turned on after the electronic tubes have warmed up, as indicated by the clicking heard as the control valves open. Third, a special programmer switch is depressed three times to provide for initial filling of the burets. Following these operations the meter will operate continuously without attention of the operator as long as battery power is available.

The photo-electronic fuelmeter has been successfully used to meter more than 300 gal of fuel on more than 3,000 fuel consumption test runs covering a total travel of more than 3,500 miles, at times with fuel temperatures in excess of 105° F.

## UNIQUE FEATURES OF PHOTO-ELECTRONIC FUELMETER

This meter incorporates several important features that make it especially valuable for road user cost studies, as follows:

1. There is no need to calibrate the meter. All the fuel that passes through the calibrated burets and is delivered to the carburetor of the vehicle is measured accurately. If, for any reason, a single count is not recorded, the counting process will stop completely and will not resume until the fault is cleared. This is an extremely valuable asset because, as long as the fuelmeter is counting, it will count and record accurately. Thus, there is no chance of accumulating masses of erroneous data before failure of the meter is detected.

2. The meter remains usable even if the automatic feature fails. The level of the fuel can be observed at all times in the burets. Should the automatic counting and refilling operations fail to function, the operator may continue to take data by observing the level of the fuel in the burets and by performing the refilling operation manually. Test runs in the field need not be discontinued should the automatic operation of the fuelmeter fail.

3. Direct reading of fuel levels to obtain extremely high precision is possible. Although this fuelmeter was constructed to record automatically each 5 cc of fuel consumption, greater precision of measurement is obtainable by visually reading the level of the fuel in the burets. Readings to within 0.2 cc are possible. This makes it practical to use the meter to measure the effect on fuel consumption of highway conditions existing over only a relatively short distance as, for example, on a curve.

4. Operation of the meter is not restricted to a limited range of flow rates. Because the meter functions inde-

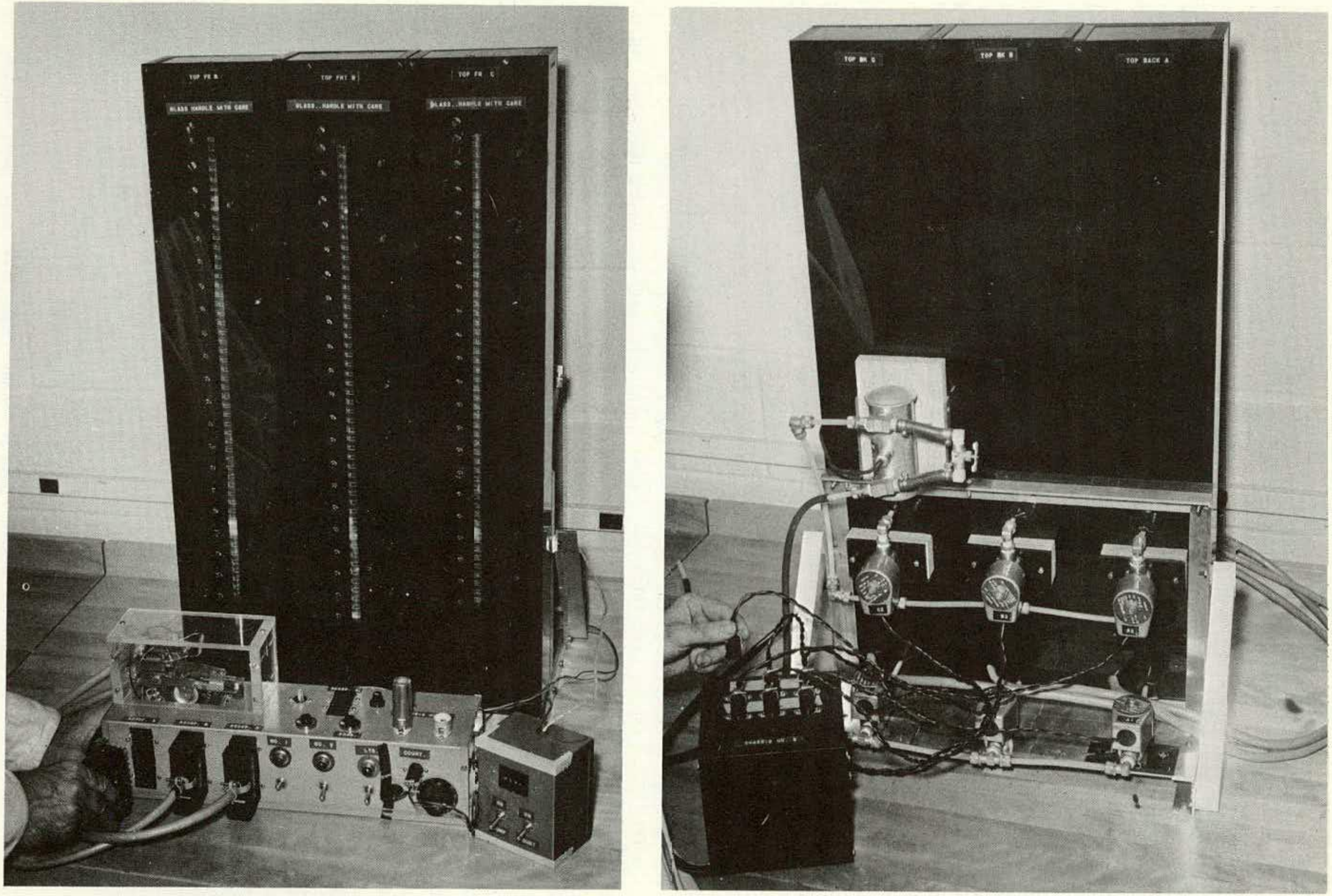

*Figure B-4. Photo-electronic fuelmeter, showing (left) buret tubes in their cases, chassis No. 1, and impulse counter; and (right) rear of buret cases, with fuel pump, refill and drain valves, and chassis No. 2.*

pendently of the rates of flow of fuel passing through it, its operation is not inhibited at extremely low flow rates, which is a drawback of certain commercial fuelmeters. The meter has operated equally well both with the engine idling and with the engine striving to accelerate the vehicle to 80 mph.

5. The meter has no moving parts that can be fouled by fuel movement. Because the flow of fuel in this meter is restricted to movement in the glass burets, the valves, and the associated tubing, there is no chance of the fuel affecting any mechanical or electrical component of the system. Furthermore, there is no chance of trapped air in the fuel line causing faulty operation. The meter is so constructed that any trapped air is automatically released during the refilling process and, consequently, is not present to cause either erroneous positioning of the floats or possible fouling of the fuel lines.

6. The meter is suitable for continuous use in any highway vehicle. Because the operation of this fuelmeter is unaffected by the normal ambient conditions experienced in the operation of highway vehicles, there is no limitation on the kind of vehicle used or the extent of its use. The meter is not influenced by normal changes of fuel temperature, pressure, or octane content. In fact, as long as the proper tubing, fittings, and valves are used, the flow of any kind of fluid could be measured with this meter. Also, the operation of the meter is not affected by the usual irregularities of normal vehicular motion, such as quick starting and stopping, moving upgrade or downgrade, rapid reversing, or entering and traversing a sharp curve.

7. Fuel consumption may be photographically recorded. By mounting a motion picture camera focused on the moving floats in the burets, a continuous photographic record of fuel consumption may be obtained. This is particularly useful when the readings of other instruments (such as vacuum gauge, speedometer, engine speed indicator, or accelerometer) are to be recorded simultaneously. Such pictures could provide complete information on engine and vehicle performance.

## SUMMARY

The photo-electronic fuelmeter has been developed to meet a specific need, that of providing a dependably accurate means of measuring the fuel consumption of motor vehicles as required for the types of fuel consumption studies called for in modern comprehensive road user cost investigations. It will record automatically with a precision that is satisfactory for most of these studies and, in addition, it includes a means of achieving much higher precision as may occasionally be needed. The accuracy of measurements by this meter is unquestioned and it will stop completely before giving erroneous readings.

This meter will facilitate much broader and more extensive investigations of motor vehicle fuel consumption costs as affected by highway factors than have been attempted in the past. The successful development of the meter is a major breakthrough in the continuing struggle to find better ways of accumulating basic information on highway user cost for better highway planning.

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